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This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

A review was made of the pavement condition of roadways constructed with lime treated soils and aggregates throughout California. This review, in conjunction with detailed investigations of selected roadways, was used to evaluate the performance of lime treated materials when incorporated into the roadway structural section. It was concluded that lime treated materials can provide a satisfactory alternative to high quality aggregate base and subbase materials. Distress or failure of lime treated materials was traced to three primary sources: nonresponsive soils, poor distribution of the lime, and inadequate design of the roadbed. Conclusions and recommendations regarding testing, design and construction practices are also presented.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

April 1976

FHWA No. D-2-14
TL No. 633324

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

A REVIEW OF THE PERFORMANCE OF
LIME TREATED ROADWAYS IN CALIFORNIA

Study made by . . . . Roadbed & Concrete Branch

Under the Supervision of . . . . John Skog

Principal Investigator . . . . Robert N. Doty

Co-Investigator . . . . Max L. Alexander

Report Prepared by . . . . Max L. Alexander

Very truly yours,

George A. Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

MLA:lrb

ACKNOWLEDGEMENTS

This is the final report for a study titled "Lime Treated Roadways" which was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

This project was begun under the supervision of Ernest Zube and principal investigator Clyde G. Gates. Until the time of their retirement from State service, Mr. Zube and Mr. Gates, along with Harry Rhud, former Materials Engineer in Highway District 03, were the principal supporters of the use of lime treated materials for roadway construction in California. The efforts of these three engineers is largely responsible for the increasing acceptance of the use of lime treated materials in California today.

Following Mr. Zube's retirement, supervision of this study was carried on by George B. Sherman and then John B. Skog, both of whom have also retired from State service. Mr. Gates' responsibilities as principal investigator were passed on to Robert E. Smith and then to Robert N. Doty. The author wishes to thank each of these men who provided direction in conducting this study and preparing the final report.

The author also wishes to express his appreciation to the many city and county engineers throughout California who cooperated in this study by providing design and construction information,

by personally assisting in field reviews, and by offering their opinions and observations based on individual experiences. Acknowledgement is also given to the field personnel of the Transportation Laboratory who, under the supervision of Martin Bianco, were responsible for the deflection surveys and the coring and sampling of projects selected for detailed investigations and to testing personnel who, under the direction of Rui Maeda, performed the physical evaluation tests on the recovered materials.

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INTRODUCTION

Lime has been used on a limited basis to stabilize or improve the structural quality of highway construction materials in California for more than two decades. The acceptance of the use of lime stabilized materials, however, has been neither immediate nor unanimous among highway engineers. As a result, the amount of lime stabilization work on State highway projects in California has increased slowly.

The increased costs of processing and transporting aggregate, along with the decreasing availability of good quality aggregates, have caused a steady increase in the need to provide a structurally suitable substitute for these untreated aggregate base and subbase materials. This has been especially true for some county road departments where funds are extremely limited and the need for improved roads is great. Because of these needs, the interest in lime treatment of locally available materials has grown steadily in California during the past fifteen years.

Increasing interest on the one hand, coupled with skepticism on the other, has led to the use of lime treated materials in several research test sections on State and FAS routes. These test sections, some of which were several miles in length, were monitored through various phases of construction and for a period of time following completion of the roadway. Although these test sections have provided considerable information regarding individual projects, they have not been comprehensive enough to provide a basis for an overall evaluation of the field performance of lime treated materials under varying environmental conditions. Thus, the objectives of this study were to evaluate the performance of lime treated roadways in all regions of California and to relate the observed performance to design and construction procedures. Each road included in this study was visually inspected for surface distress. The amount of maintenance work made apparent by patches and overlays was taken into consideration along with existing distress in the form of potholes, rutting and cracking. This visual inspection was supplemented with detailed investigations of the in-place structural section materials on several selected projects.

To provide data from a broad range of materials over a large geographical area, many FAS routes and county roads were included in the study. A few city streets were also included.

The roadway condition survey and detailed investigations of selected projects, along with discussions with design and construction personnel in many agencies, have provided considerable insight into the use of lime treated materials for road construction. Discussions with representatives of various local agencies also pointed out a weakness when evaluating projects on the basis of a surface condition survey alone. One county road in the San Joaquin Valley area required resurfacing after 7 years of service while two other roads in the same vicinity were rated by the condition survey as being in extremely poor condition. County personnel, however, consider the performance of these roads to be completely satisfactory in that the maintenance work, even though not eliminated, was significantly less than the effort generally required when roads were constructed using similar material and no lime treatment.

It must also be realized that much of the early lime stabilization work throughout California was done as a "last resort" effort to economically correct severe structural problems or extreme exposure to ground water. Often, this work was done without benefit of preliminary testing or design criteria. Under such conditions, it can only be stressed that lime treatment is not a "cure all" for every situation and an engineering approach to its use must be utilized if a high degree of success is to be expected.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived from data and information gathered from this study.

1. The stability of substandard aggregates can often be significantly improved by treatment with lime.

2. Certain soils can be effectively used as a base or subbase in the roadway structural section if treated with lime.

3. Distress or failure of lime treated materials in a roadway structural section can generally be traced to one or more of three primary sources:

   a) Attempted treatment of nonresponsive materials.
   b) Poor uniformity of the lime distribution.
   c) Inadequate structural section design.

4. Adherence to the asphalt concrete surface thickness designated by the design formula is essential to the satisfactory performance of lime treated roadways.

5. Any of the high calcium lime products which meet the minimum calcium hydroxide content requirements included in the January 1975 Standard Specifications of the California Department of Transportation can be used successfully for road construction.

6. Lime treated materials can be adversely affected by repeated wetting of the exposed surface, or by excessive drying, or alternate wetting and drying of the in-place material, prior to completion of the cementing process.

7. Shrinkage cracking is a common occurrance in lime treated materials. The severity of the cracking is often increased, however, when rapid and excessive drying occurs.

8. Successive layers of lime treated material often do not bond together, thus creating potential slippage planes.

9. The ultimate structural value of lime treated materials is not always correctly measured by the R-value test. The ion exchange which alters the soil characteristics and improves the R-value may not be permanent if cementing does not occur.

10. The current California design procedure provides a structurally adequate roadway when responsive materials are treated with lime. It does not, however, take full advantage of the high compressive strengths developed by lime treating some materials.

The following recommendations are offered on the basis of the foregoing conclusions.

1. Lime treatment of sub-standard aggregates and materials already in place in the roadway should be given consideration as a viable alternative when constructing new roads and reconstructing existing roads.

2. Native soils which respond favorably to lime treatment should be given consideration for incorporation into the roadway structural section.

3. It is imperative that sufficient preliminary testing be done to evaluate individually each material's response to lime treatment.

4. The asphalt concrete thickness required per the design procedure should be closely adhered to.

5. The specifications for lime treatment should be modified to allow the use of various forms of lime which meet the minimum calcium hydroxide requirements and can be dispersed uniformly within the material being treated.

6. Lime Treated materials must be protected from excessive drying. The surface of the compacted layer should be covered as soon as possible after compaction with the next layer of the structural section or a curing seal. When it becomes necessary to keep the surface of the lime treated material moist by the application of water, traffic should not be permitted on this moist material.

7. Traffic should also be prohibited from using the lime treated material until the material has gained enough strength to resist deformation under loading. A research project should be initiated to develop a simple method of evaluating the load bearing capacity of in-place materials.

8. The maximum lift thickness for lime treated soils should be increased from 6 to 12 inches when the contractor demonstrates that his equipment and method of operation will provide uniform distribution of the lime and the required densities.

9. A minimum lift thickness of 4 inches should be required to eliminate thin layers and reduce the number of potential slippage planes within the total thickness of lime treated material.

10. An unconfined compressive strength test should be used to evaluate the ultimate structural value of lime treated materials. When it is established that a material is suitable for lime treatment, the structural section should be designed to effectively utilize the potential of the lime treated material.

11. The structural value of lime treated materials, expressed and applied to the California design formula in terms of gravel equivalent value, should be established on the basis of unconfined compressive strength. High strength materials should be assigned greater value than low strength materials. A research study is currently in progress to evaluate the strengths that can be

achieved when lime is mixed with various soils. This work should provide more complete data for establishing gravel equivalent values of lime treated soils based on unconfined compressive strengths.

IMPLEMENTATION

Many of the findings and recommendations included in this report have already been incorporated into more recent lime treatment projects.

Revised specifications permitting the use of granular quicklime have been prepared and submitted to the specifications committee. Although not yet included in the Standard Specifications, these specifications have been used on several individually approved State projects as well as county projects.

Recent reconstruction work on California Route 45 incorporated several of the proposals recommended in this report. On this project, existing roadway materials, including asphalt concrete, aggregate base and the underlying clayey soil, were treated with quicklime for use as a base course. The total 0.83 ft. thickness of the lime treated base was mixed and compacted as a single layer with no difficulties in meeting specifications.

An unconfined compressive strength test for use with lime treated materials has been developed by the Transportation Laboratory. The procedure and its application to the design and control of lime treated materials have not yet been officially adopted; however, the test is being used in research studies and has been distributed to other agencies upon request. The application of data from this test to structural section design will be evaluated upon completion of a current laboratory study of the strengths of lime treated soils.

BACKGROUND INFORMATION

The first recorded use of hydrated lime as a soil stabilizing agent by the California Division of Highways was in 1921-22. At that time a section of road in Solano County between Rio Vista and Denverton was used as an experimental roadway to study methods of stabilizing adobe subgrades. Twelve test sections were constructed using various percentages of portland cement, hydrated lime, limestone dust or asphaltic oil to modify the subgrade soil. Adjacent sections were also constructed with 4 inches of gravel over the untreated soil. A pavement condition survey two years after construction revealed that none of the modified soils prevented cracking of the 5 inch thick PCC pavement that had been placed. It was concluded at that time that the 4 inch layer of gravel was a more efficient, and much less expensive, method of reducing pavement damage caused by unstable subgrade materials.

Lime stabilization work in California was then confined to the laboratory until the late 1940's. In 1948, lime was used on two separate projects in the central Sierra Nevada area to reduce the plasticity of existing, or readily available, base materials. A short-term performance analysis of these roads after two years of service indicated that the addition of lime had improved the quality of the base material and that these test sections were holding up better than adjacent sections constructed with untreated base materials (1).

As a result of the apparent success of these two projects, several individuals, both in the District and in the Materials and Research Department, became advocates of lime stabilization. During the 1950's lime stabilization was used for numerous maintenance projects in Highway District 03, but few new construction projects included lime treated materials until the late 50's and early 60's. Because of this slow gain in acceptance, construction techniques for lime stabilization remained relatively crude and specifications were practically nonexistent for both the lime and the completed mixture of lime and soil. Records indicate that prior to 1959 the lime was simply described as "hydrated lime" or, in many instances, as "agricultural lime." Consequently, at times a waste lime from sugar refineries or acetylene manufacturing plants was used.

With the increased interest in lime stabilization, several experimental roadway projects were constructed and evaluated during the late 50's and early 60's (2). In most cases, the lime stabilization work on these experimental projects was apparently effective per short-term evaluation; however, there remained a need for a long-term evaluation of the performance of lime treatment under various conditions and with several types of soils. The purpose of this study was to evaluate the condition of roadways throughout the State which had been constructed with lime treated soils and aggregates and then determine the factors which may have influenced the success or failure of these roads through a comprehensive investigation of the in-place materials on selected roads.

It was originally intended that only State and FAS projects would be included. Much of the early use of lime on State routes, however, was done as maintenance work on short sections of road as mentioned previously. As a result, design and construction data were not available and the limits of the areas could not be identified. In order to provide a broader base for the performance evaluation, all California counties and some cities were contacted regarding their use of lime stabilized materials.

Eventually, over 150 individual lime treatment projects were identified throughout the State. Many of these, however, were not suitable for inclusion in this study for one reason or another. Some had been reconstructed or abandoned since construction, while many others were too new to provide meaningful performance data. In some cases, the only construction records were the memories of personnel directly involved with the construction of the project.

In the final analysis, seventy separate roadway sections were selected for this study. These roadways have been separated into two primary groups, those which included lime treated material as a base directly under the asphalt concrete surfacing and those which had a lime treated subbase, a gravel base, and an asphalt concrete surfacing. Several roads were also observed which were constructed with a cement treated base over the lime treated material. These roads were not included in the study, but none showed any evidence of distress when inspected.

Although many miles of freeway constructed in recent years have included lime treated basement soils, these were not included in this study. These freeways were constructed using PCC pavement, cement treated base, aggregate subbase and lime treated soils. Lime treatment on these projects was performed to eliminate or reduce excessive expansion in the upper portion of the soil, to provide additional cover over the untreated expansive materials, and to create an impervious barrier to prevent surface water from reaching the expansive soils. Because of the purpose of the lime treatment and the rigidity of the structural section, these freeway sections did not lend themselves to the scope or methods of this study. It may be adviseable, however, to make a separate evaluation of the performance of lime treated soils under PCC pavements.

EVALUATION OF ROADWAY PERFORMANCE

Two main factors were considered when evaluating the performance of the roadways. One was the physical condition of the road after being subjected to traffic for a substantial period of time. The second was an estimation of the adequacy of the roadway structural section based on currently accepted design criteria.

Visual surveys were made to evaluate and compare the surface conditions of the roadways included in this study. The estimated percentage of the total roadway surface affected by distress was used to assign ratings of good, fair, poor, or extremely poor.

Roadways on which six percent or less of the total travel lane surface area was affected by visual distress or patching were arbitrarily assigned a condition rating of "good". When the affected area amounted to seven to twelve percent, a rating of "fair" was assigned and a rating of "poor" was assigned when thirteen to twenty-five percent was affected. Roads which showed evidence of distress over more than twenty-five percent of the total area were rated as "extremely poor". Under this system, isolated problems which could have originated from numerous sources such as inadequate construction control or uncorrected local foundation conditions would not have an over-bearing effect on the evaluation of the performance of the designed structural section.

Exact measurements of the surface areas affected were, of course, impractical. It was therefore necessary to adopt some basic guidelines for determining the sizes of these areas. The width of the distressed area was designated as being either full lane width or half lane width. Under this system, distress in one wheel path, which might actually be only a foot wide, was considered to cover half the travel lane. If both wheel paths were distressed the full width of the travel lane was considered to be affected.

Longitudinal and transverse cracking which are normally attributed to shrinkage were not considered to be distress unless accompanied by other evidence such as rutting or alligator cracking. Distress judged to have originated in the surfacing or foundation layers was also noted but not included in the performance ratings. Examples of excluded failures would be obvious fill subsidence or asphalt stripping.

The adopted rating system proved to be adequate for characterization of the surface condition of the various roads.

A smaller sampling of roads was later selected for detailed materials investigations. Deflection measurements were used to add information to the performance evaluations, and test holes were used to determine causes of isolated problem areas as well as differences in the performance of various roads. Both "good" and "poor" roads were included in this detailed investigation.

The California design procedure for flexible pavements (3) was used to estimate the adequacy of each roadway structural section included in this study. This procedure can be used to establish the required thickness of each layer in the structural section based on the destructive effect of the predicted traffic and the load bearing capacity of each layer of material. The destructive effect of traffic is expressed as a numerical value referred to as the traffic index (TI). For design purposes, a traffic index of 5 is normally considered to be a minimum practical value and applies to lightly travelled rural roads. At the opposite extreme, the traffic index of some heavily traveled interstate routes may be as high as 13; however, 8.5 was the highest value assigned to any road included in this study. The load bearing capacity or structural quality of soils and aggregates is measured in terms of resistence (R) value (4). Crushed gravels and some stabilized soils may have R-values approaching 90 while some "heavy" clays may have R-values of less than 5.

The required thickness of the total roadway structural section and each of the component layers are first determined and expressed in terms of gravel equivalence (GE) or, in other words, the thickness of gravel that would be required to carry traffic over the underlying material. The GE value is then converted to actual thicknesses of the various structural section components based on assumed slab or tensile strengths which are expressed as gravel factors (G_f). The current California design procedure includes a gravel factor of 1.2 for all lime treated materials. This assumes that one foot of lime treated material will have the same value in a roadway structural section as 1.2 feet of gravel. For comparison, aggregate base, which contains a minimum of 25% crushed particles, is assigned a gravel factor of 1.1 and cement treated base, consisting of a graded aggregate and portland cement (7-day lab compressive strength of 750 psi) is assigned a gravel factor of 1.7. The gravel factor of asphalt concrete surfacing varies from 1.5 to 2.5 depending on the traffic index of the road with lower gravel factors used for higher TI's.

Some counties in California allow higher gravel factors for lime treated materials than are designated in the California design procedure. However, in order to compare the structural quality of all roads on an equal basis, the 1.2 gravel factor was applied to each road regardless of the design criteria actually used.

In some cases, the structural section thicknesses were based on experience, economics and "engineering judgement" rather than a design formula. An effort was made to include these projects in the study, but only relative performance evaluations were possible when traffic conditions and/or the R-value of basement soils were not known.

Most of the roadways included in this study were designed for a ten-year service life. In other words, the structural section should have been sufficient to carry the projected traffic for ten years without requiring major reconstruction or repairs. It was therefore desirable to either make the performance evaluation at the end of this design life or at least be able to extrapolate the observed performance to a ten-year life. The surface condition of many of the projects was observed several times over a period of several years. These periodic reviews provided some insight into the rate of deterioration taking place and provided a basis for extrapolating the performance to a ten-year life.

Lime Treated Subbase

Of the roads identified and included in this study, twenty-four were constructed using lime treated materials as a subbase. The structural sections were completed by adding an untreated aggregate base and an asphalt concrete surfacing.

The available materials and traffic data for each of these roads are listed in Table 1. Also included in Table 1 are the structural section thicknesses which would be necessary to meet current design standards and the structural sections actually constructed. Table 2 provides a summary of the lime treated material used on each project and an evaluation of the actual or projected surface condition of the roadway after 10 years

Table 1

Design of Roadways Incorporating Lime Treated Material as a Subbase

Project	Agency	Traffic Index	R-value Basement Soil	Thickness Required by Design: Surface GE	Thickness Required by Design: Surface Actual	Thickness Required by Design: Total GE	As Built Structural Section: Surface Stage 1	As Built Structural Section: Surface Stage 2	As Built Structural Section: AB	As Built Structural Section: LTS	As Built Structural Section: Total GE
S1	FAS	6.5	5	0.42	0.17	2.00	0.21 AC		0.50	0.50/0.50AS	2.10
S2	FAS	7.0	32	0.45	0.21	1.50	0.12 AC		0.50	0.50	1.40
S3	FAS	7.0	6	0.45	0.21	2.10	0.12 AC		0.50	1.00	2.00
S4	County	<5.0	16	0.32	0.13	1.40	dbl.seal coat		0.50	1.00	1.75
S5	County	6.7	15	0.43	0.20	1.80	0.17 AC		1.00	0.50	2.10
S6	County	6.0	5	0.38	0.16	1.80	0.17 AC		0.50	0.90	2.00
S7	County	6.0	5 (a)	0.38	0.16	1.80	0.12 AC		0.50	1.00	2.00
S8	FAS	7.5	3	0.48	0.24	2.30	0.17 AC		0.50	1.00	2.10
S9	County	6.5	5 (a)	0.42	0.20	2.00	0.17 AC		0.50	0.75	1.80
S10	County	8.0	7	0.51	0.25	2.40	0.33 AC		1.00	1.00	2.95
S11	County	8.0	22	0.51	0.25	2.00	0.33 AC		1.17	1.00	3.20
S12	County	8.0	22	0.51	0.25	2.00	0.33 AC		1.17	1.00	3.20
S13	County	6.7	15	0.43	0.20	1.80	0.17 AC		0.75	0.75	2.10
S14	County	7.0	5	0.45	0.21	2.10	0.25 AC		0.50	0.92	2.25
S15	County	7.5	5	0.48	0.24	2.30	0.17 AC		0.55	1.10	2.35
S16	County	7.0	5 (a)	0.45	0.21	2.10	0.25 AC		0.55	0.85	2.10
S17	County	6.5	5 (a)	0.42	0.20	2.00	0.25 AC		0.50	0.75	2.30
S18	County	6.0	22	0.38	0.16	1.50	0.25 AC		0.50	0.92	2.25
S19	County	6.6	5	0.42	0.20	2.00	0.33 AC		0.50	0.42	1.75
S20	County	7.2	10	0.46	0.21	1.80	0.25 AC		0.67	0.50	1.85
S21	County	7.0	5	0.45	0.21	2.10	0.33 AC		0.58	0.50	1.95
S22	County	7.8	11	0.50	0.25	1.75	0.25 AC		0.50	0.83	2.05
S23	County	7.7	14	0.49	0.24	2.10	0.33 AC		0.50	0.50	1.80
S24	County	5.5	5	0.35	0.15	1.70	oil & gravel	.17	0.50	0.50	1.50

GE = gravel equivalent
AC = asphalt concrete
RMAS = road mixed asphalt surfacing
AB = aggregate base
AS = aggregate subbase
LTB = lime treated base
LTS = lime treated subbase
IB = imported base
(a) = assumed

Table 2

Materials and Surface Condition Information for Roadways Constructed with Lime Treated Material as a Subbase

	Material Treated				Surface Condition Survey						
			Lab R-value		Cracking						
Project	Type	%Lime	Before	After	Longt.	Trans.	Allig.	Rutting	Pothole or Patch	Overall* Condit.	Years'** Service (If other than 10)
S1	AS	2	21-74	73-84						Excellent	-
S2	soil & agg.	4	6-74	41-82	✓	✓	✓	✓	✓	Good	-
S3	soil & agg.	4	6-74	41-82	✓	✓	✓	✓	✓	Good	-
S4	soil	4(S)	16	78			✓			Poor	-
S5	soil		15		✓			✓		Fair	-
S6	soil	4	5	65			✓	✓	✓	Extremely Poor	-
S7	soil & agg.	4	5 min.	60 min.			✓	✓		Fair	-
S8	soil	4	3	74-81						Good	-
S9	soil	4(S)		80					✓	Fair	-
S10	soil	4	7	81						Good	-
S11	soil	3	22	82						Good	-
S12	soil	3	22	82						Good	-
S13	soil		15		✓			✓		Fair	-
S14	soil	4(S)	5 min.	50 min.	✓		✓		✓	Extremely Poor	7
S15	soil & agg.		5 min.	60 min.			✓		✓	Poor	-
S16	soil	4			✓	✓				Fair	8
S17	soil	4		76	✓	✓				Good	8
S18	soil	4	22	72-81						Excellent	-
S19	soil		5		✓					Good	9
S20	soil	2-3(Q)	10-68				✓			Fair	9
S21	soil	2½-3½(Q)	5-21		✓					Excellent	9
S22	soil	2½-3½(Q)	6-27							Excellent	8
S23	soil	2½-3½(Q)	14-20							Excellent	7
S24	soil	4								Good	-

(S) = sludge lime

(Q) = quicklime

*Actual or interpolated condition at end of 10 year service.

**Actual years of service if less than 10 at the end of the study, or if more than 10 when initial survey was made. The years of service prior to a rating of "extremely poor" are noted even though the road may have been reviewed at a later date.

of service. Included in this condition survey is a list of the types of distress or cracking observed and an assigned condition rating. The surface conditions after various lengths of time in service are presented in Figure 1. The length of service time prior to resurfacing, reconstruction, or coring in conjunction with this study are also shown.

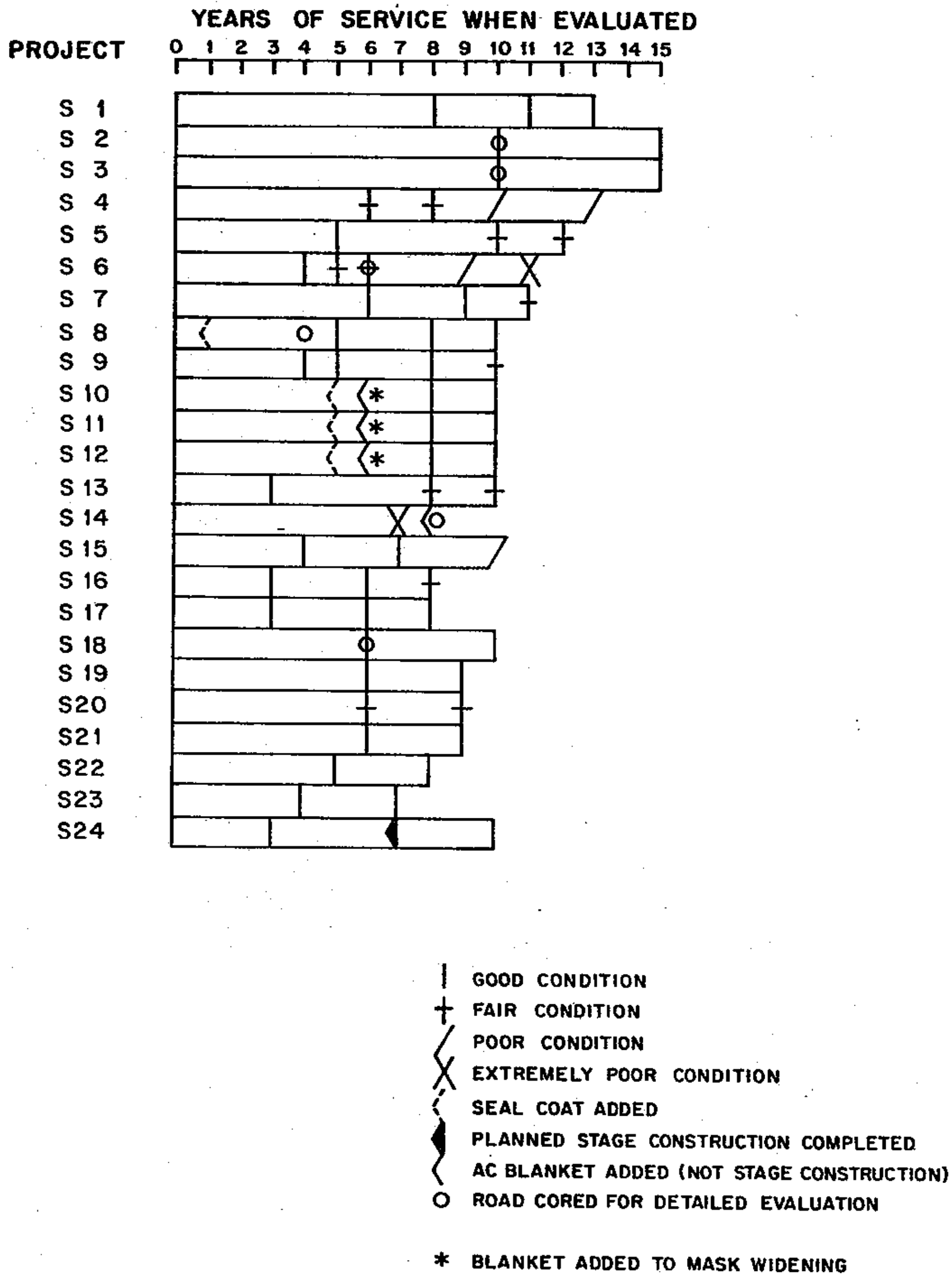
The thickness of asphalt concrete required by design criteria can be compared with actual asphalt concrete thicknesses in Table 1. This comparison reveals that nine of the 24 roads were constructed with the surfacing deficient by .07 ft. or more. In some cases less than half the required surfacing was placed. It was often intended, however, that the surfacing would be placed in stages with only a portion of the required thickness being placed initially to carry current traffic and the remainder to be added at some future date. In Figure 1, asphalt concrete blankets which completed stage construction are identified separately from resurfacing made necessary by other reasons such as distressed or deteriorating pavements.

Seal coats are also added for a variety of reasons which may or may not indicate an inadequacy in the structural section. A seal coat is often used to seal and cover cracking in the pavement while at other times it may be used as a routine preventative maintenance procedure or to improve the surface texture of the road. Unless other indications of distress were apparent, it was assumed that seal coats were added for some reason other than to cover a structural deficiency.

The majority of the 24 roads which were constructed using lime treated material as a subbase were found to be in generally good condition. All but four of the roads were in fair to excellent condition at, or near, the end of their ten year design life. Two roads were in poor condition and two were rated as being in extremely poor condition. Of these latter

Figure 1

PERFORMANCE EVALUATION OF ROADWAYS INCORPORATING LIME TREATED MATERIALS AS A SUBBASE



two, one was in extremely poor condition when first reviewed after seven years of service and a new asphalt concrete surface was added one year later.

Localized distress was also observed in a few of the other roads. Although the distress was sometimes severe, the total area affected was quite small and the overall condition was rated as fair to good.

A review of the structural section data in Table 1 indicates that the actual gravel equivalent thicknesses of the 24 different roads varied from 0.3 foot less than required by the current design procedure to as much as 1.2 feet more than required. A comparison of the current design thicknesses with the actual as-built thicknesses in Figure 2 fails to show a definite correlation between the structural section and the performance rating. Each of the four roads constructed with 0.5 ft. or more thickness than required was in good condition but all of the roads which were rated as being in poor or extremely poor condition were also constructed with an "adequate" design thickness or better. Only one of the nine roads constructed with less than "adequate" total thickness was judged to be in fair condition while all of the remainder were in good condition.

A comparison of the current thickness design requirements and as-built thicknesses of the asphalt concrete in Figure 3 shows that the performance of this group of roads is influenced to some degree by the adequacy of the surfacing. All of the roads which included the additional asphalt concrete required by the design procedure as a safety factor were in good condition. Eighty two percent of the roads which were constructed within $\pm$ .05 ft. of the "design" asphalt concrete thickness were in fair to good condition while 60% of the roads which were deficient in asphalt concrete thickness by more than .05 foot were in fair to good condition.

Figure 2

DEVIATION FROM STRUCTURAL SECTION DESIGN THICKNESS AND THE EFFECT ON PAVEMENT PERFORMANCE (LIME TREATED SUBBASE)

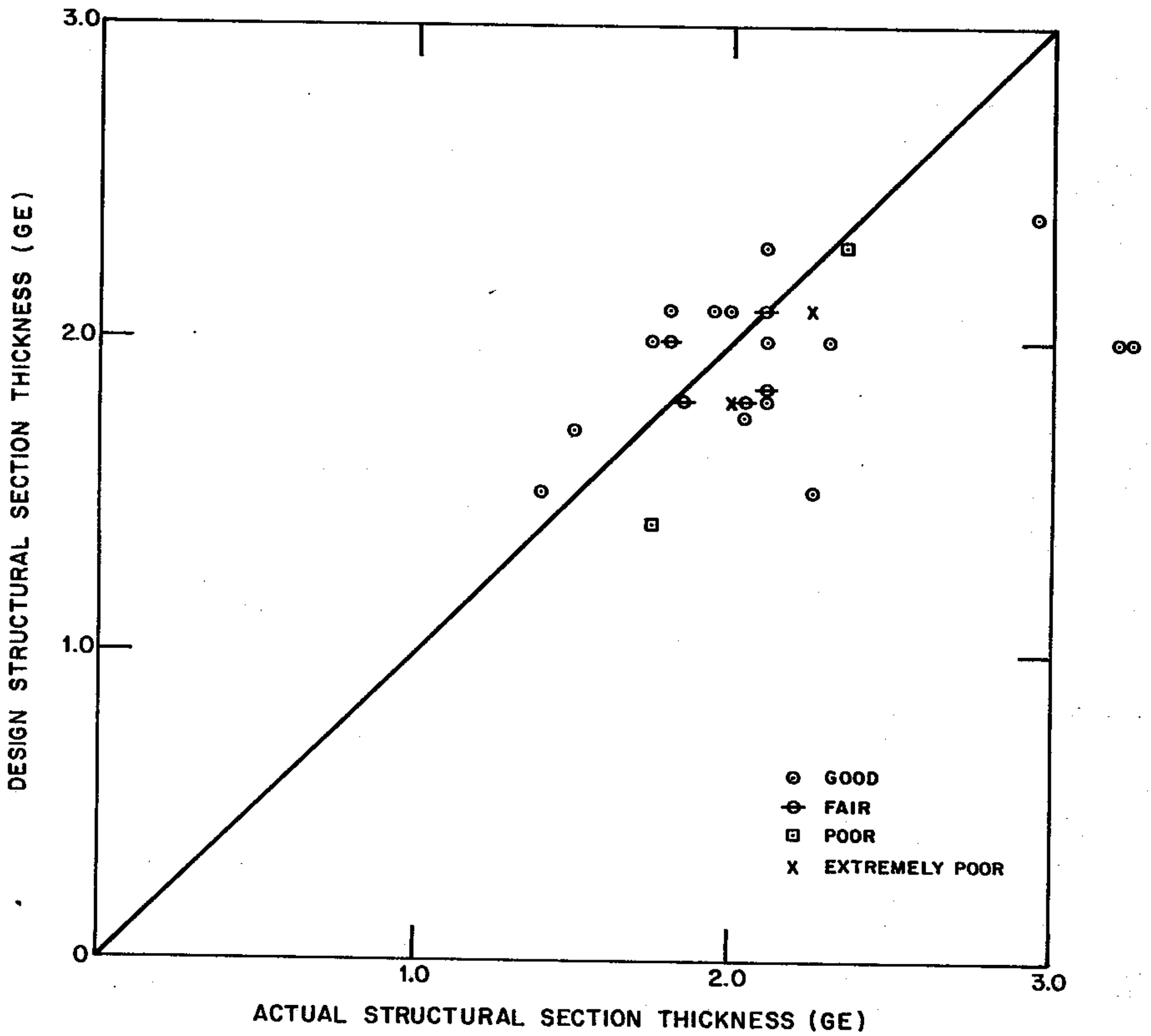
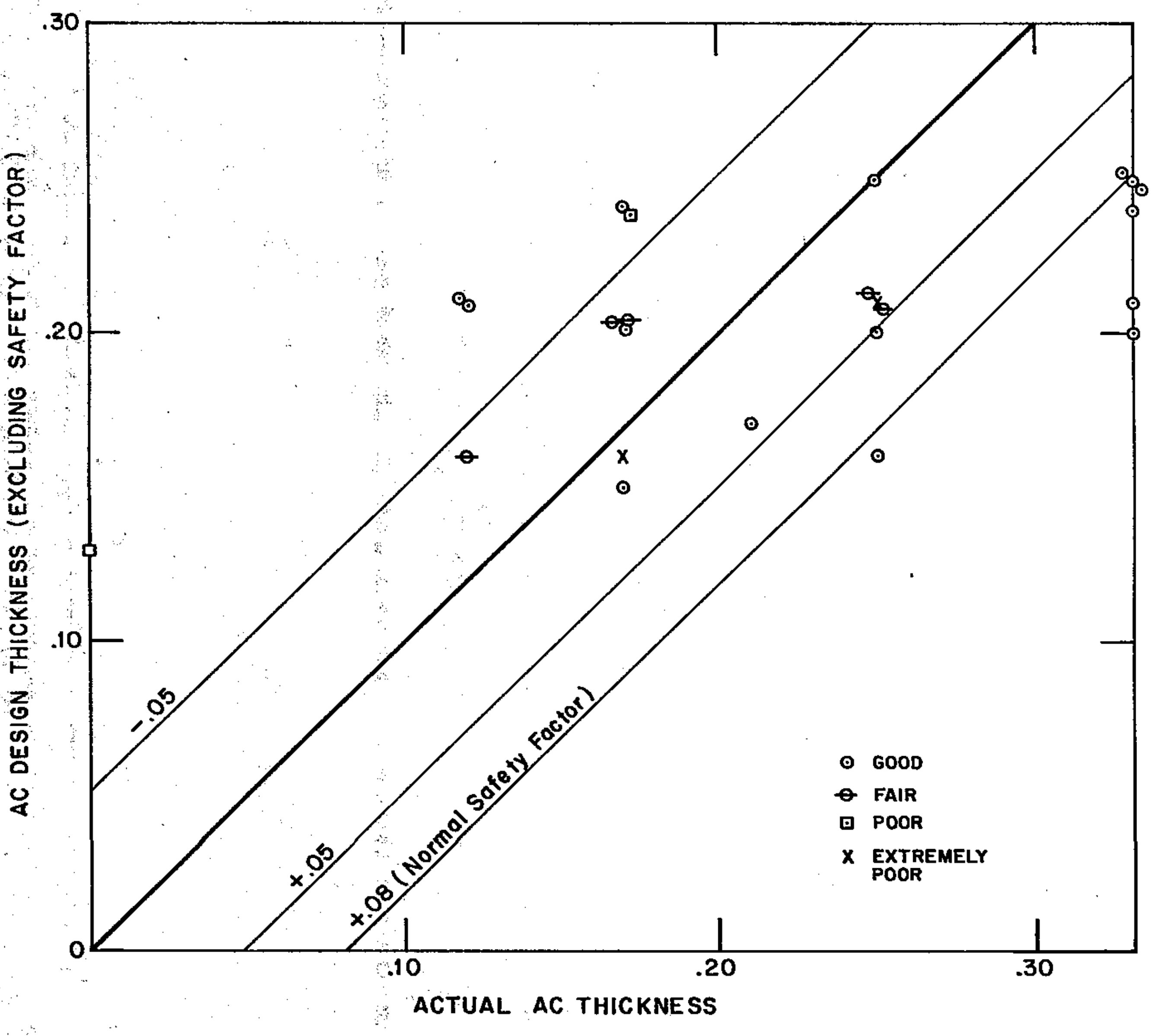


Figure 3

DEVIATION FROM ASPHALT SURFACING DESIGN THICKNESS AND THE EFFECT ON PAVEMENT PERFORMANCE (LIME TREATED SUBBASE)



Six roads from this group of 24 were selected for coring and a detailed evaluation of the in-place materials. Projects S6 and S14 were selected for this phase of the study because of the widespread distress which they exhibited. Project S18 was selected because it had no visible distress. The remaining three projects - S2, S3 and S8 - were in generally good condition but each contained occasional areas of distress.

The observations and findings from these detailed investigations are summarized in Appendix A. In general, it was concluded that most of the observed distress was caused, at least in part, by construction variables such as nonuniform lime distribution, aggregate base thickness deficiencies, and excessive water at the time of or shortly after construction. Based on the surface condition survey previously presented and discussed, and the findings from the detailed investigation of the selected roads included in Appendix A, it was concluded that lime treated materials can be used effectively as a substitute for aggregate subbase in the roadway structural section.

Lime Treated Base

A total of fifty-three sections of road which were constructed with lime treated materials as a base directly under the surfacing course were included in this study. Eighteen of these were constructed with lime treated aggregates while the remaining 35 were constructed with lime treated soils. In a few cases, two different structural sections were used on the same construction project to satisfy design requirements for varying basement soils. In three other cases, identical structural sections were constructed on adjacent or near-by sections of the same road. For either of these situations, each identifiable section of road was reviewed and evaluated separately.

The treated aggregates varied from commerically available aggregate base rock which fell short of standard specification requirements to gravel deposits taken from selected areas within the right of way. In some cases existing roadway materials, including the asphalt concrete and aggregate base materials, were scarified, mixed with lime, and recompacted for the base course. In most cases, these materials had R-values above 50 prior to being treated with lime.

The majority of the materials treated in the remaining projects were native soils having R-values of less than 30 prior to being treated with lime.

Because of the broad range in the types of materials being treated with lime and used as a base course, the roads discussed in this section were divided into two catagories, those which were constructed with lime treated aggregates and those which were constructed with lime treated soils.

Lime Treated Aggregate Base

The design data and structural section thicknesses for the eighteen roads constructed with lime treated aggregate as a base are tabulated in Table 3. A summary of the lime treated material used on each project and an evaluation of the actual or projected surface condition of the roadway after 10 years of service are listed in Table 4. The surface conditions after various lengths of time in service are presented in Figure 4. The length of service time prior to resurfacing, reconstruction, or coring in conjunction with this study are also shown in Figure 4.

A comparison of the required (by design criteria) and actual structural section thicknesses shown in Table 3 indicates that all but three of these roads met or exceeded the design criteria. It must be pointed out, however, that in several cases traffic and/or basement soil data were not available and it became necessary to make assumptions for these values. In a few instances, the R-values of the basement soils were deduced by assuming that the constructed structural section was correct and backing through the design formula. Assumed traffic data are based on adjacent or near-by comparable roads where traffic volumes had been established. All assumed values in Table 3 are identified in the appropriate column.

All of the roads except one were found to be in good to fair condition after 10 years of service or at the time of the latest review. Eleven had been resurfaced with an asphalt concrete blanket before the end of the 10 year planned life but eight of these were planned stage construction so the resurfacing cannot be interpreted as indicating poor service. The blanket added to another, although not specified as stage construction, only brings the total surfacing up to design standards without the full safety factor thickness added. No records or other evidence were found to indicate that any of the above roads were distressed in any way at the time the additional surfacing was added.

Projects BA4, BA5, and BA7, on the otherhand, all had visible distress at the time they were resurfaced.

Comparisons of the design structural section thicknesses with the as-built thicknesses are presented in Figure 5. Only three roads were deficient in total structural section thickness. It was one of these structurally deficient roads which was found to be in extremely poor condition after nine years of service.

Table 3

Design of Roadways Incorporating Lime Treated Aggregate as a Base

Project	Agency	Traffic Index	R-value Basement Soil	Thickness Required by Design: Surface GE	Thickness Required by Design: Surface Actual	Thickness Required by Design: Total GE	As Built Structural Section: Surface Stage 1	As Built Structural Section: Surface Stage 2	As Built Structural Section: LTB	As Built Structural Section: Subbase	Total GE
BA1	State	-	-	-	-	-	Seal Coat		0.75		
BA2$_1$	State	7	46	0.45	0.21	1.20	Pen. Treat.	0.17	0.50	0.33 IB	1.32
BA2$_2$	State	7	26	0.45	0.21	1.65	Pen. Treat.	0.17	0.50	0.67 IB	1.70
BA3	State	7.1	25	0.45	0.21	1.70	0.17		0.50		0.89
BA4	FAS	7.2	30	0.45	0.21	1.60	0.25		1.00		1.74
BA5	State	6.5	40	0.42	0.20	1.25	0.17		0.50		.96
BA6$_1$	FAS	7.0	23	0.45	0.21	1.72	0.12	0.15	0.50	0.83 IB	2.09
BA6$_2$	FAS	7.0	34	0.45	0.21	1.47	0.12	0.15	0.50	0.33 IB	1.54
BA7	State	8.5(a)	70*	0.55	0.30	0.82	0.25		0.67		1.27
BA8	State	6.5	26(a)	0.42	0.20	1.56	0.17		1.00		1.56
BA9	State	7.0	29	0.45	0.21	1.58	0.10	0.08	0.50	0.50 IB	1.54
BA10	State	7.0	45	0.45	0.21	1.23	0.17	0.08	0.67		1.34
BA11	FAS	7.5	5	0.50	0.25	2.27	Chip Seal	0.25	0.50	1.00 selected	2.10
BA12	County	6(a)	36(a)	0.40	0.17	1.21	0.17		0.50	0.25 selected	1.21
BA13$_1$	State	6.7	20(a)	0.43	0.20	1.64	0.25		0.50	0.50 in-place gravel	1.64
BA13$_2$	State	6.7	20(a)	0.43	0.20	1.64	0.25		0.50	0.50 in-place gravel	1.64
BA14	State	6.5(a)	26(a)	0.42	0.20	1.54	0.17		1.00		1.54
BA15	FAS	6.0	22	0.40	0.17	1.50	0.13	0.17	0.67		1.50

GE = gravel equivalent
AC = asphalt concrete
RMAS = road mixed asphalt surfacing
AB = aggregate base
AS = aggregate subbase

LTB = lime treated base
LTS = lime treated subbase
IB = imported base
(a) = assumed

* = R-value of in-place when cored.

Table 4

Materials and Surface Condition Information for Roadways Constructed with Lime Treated Aggregate as a Base

	Material Treated				Surface Condition Survey						
			Lab R-value		Cracking				Pothole	Overall*	Years'** Service
Project	Type	%Lime	Before	After	Longt.	Trans.	Allig.	Rutting	or Patch	Condit.	(If other than 10)
BA1	Selected	5	-	-						Good	18
BA2$_1$	IB	3	63-77	69-81	✓	✓	✓	✓	✓	Poor	16
BA2$_2$	IB	3	63-77	69-81	✓	✓	✓	✓	✓	Poor	16
BA3	Selected	5	34-69	62-91	✓		✓		✓	Fair	11
BA4	Gravel	3	37-62	80-88		✓				Good	-
BA5	Native	3-4	40-60	78-82			✓	✓		Extremely Poor	9
BA6$_1$	IB	4	60 min.	79-84						Good	-
BA6$_2$	IB	4	60 min.	79-84						Good	-
BA7	Selected	5	65 min.	77-85	✓		✓			Fair	-
BA8	Exist Base & Surf					✓				Good	9
BA9	Exist Base	5	48-72	77-79	✓	✓				Good	-
BA10	Exist Base Class 3 AB		70-78	78-83			✓		✓	Good	-
BA11	Selected (D.G.)	3.5	55-77	80+						Good	-
BA12	Selected (D.G.)				✓	✓	✓			Fair	-
BA13$_1$	Exist Road	3-5		80+		✓			✓	Good	-
BA13$_2$	Exist Road	3-5				✓			✓	Good	-
BA14	Exist Road	4	38-51	77-82		✓				Good	-
BA15	Exist Road	4	22-75	47-83			✓	✓	✓	Fair	9

(S) = sludge lime

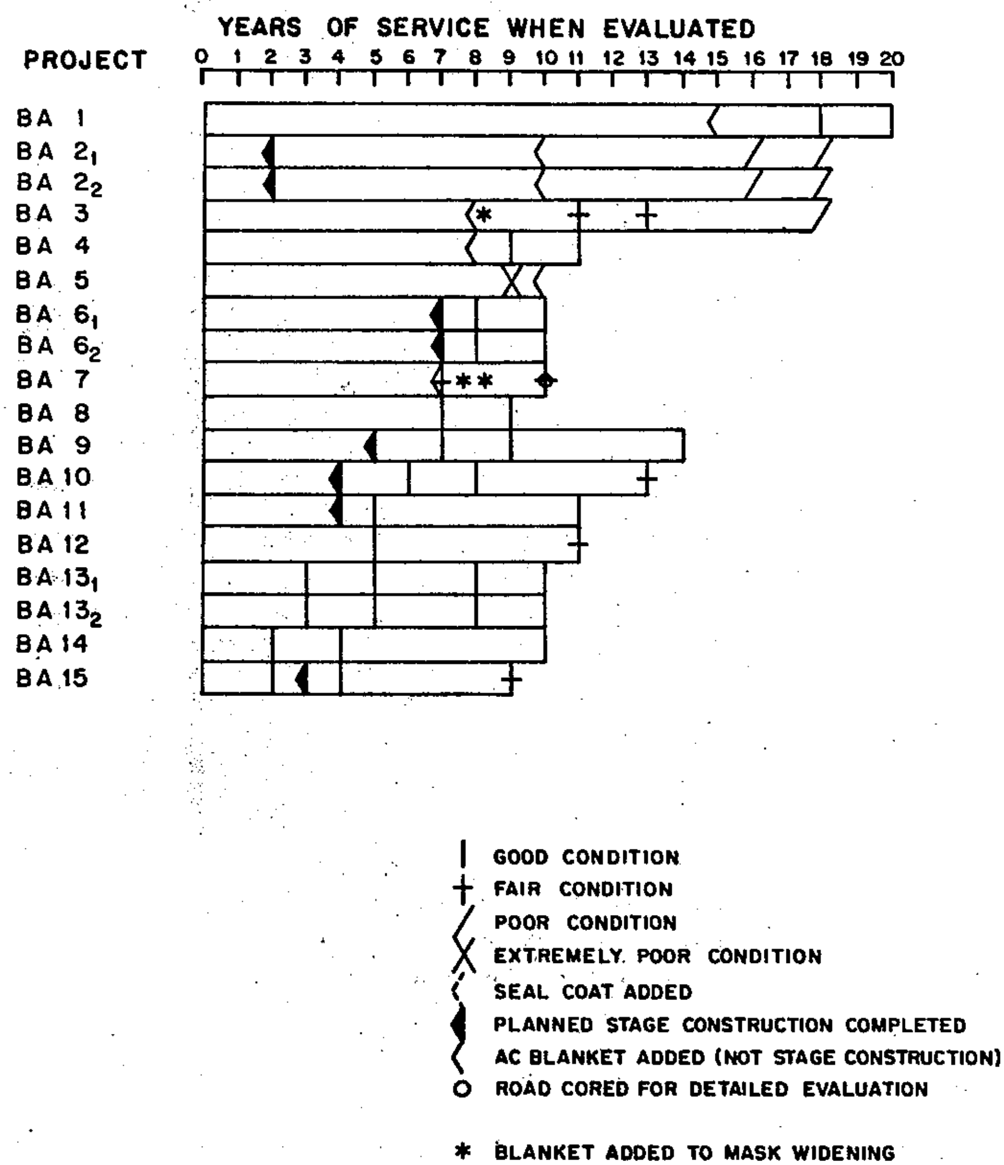
(Q) = quicklime

*Actual or interpolated condition at end of 10 year service.

**Actual years of service if less than 10 at the end of the study, or if more than 10 when initial survey was made. The years of service prior to a rating of "extremely poor" are noted even though the road may have been reviewed at a later date.

Figure 4

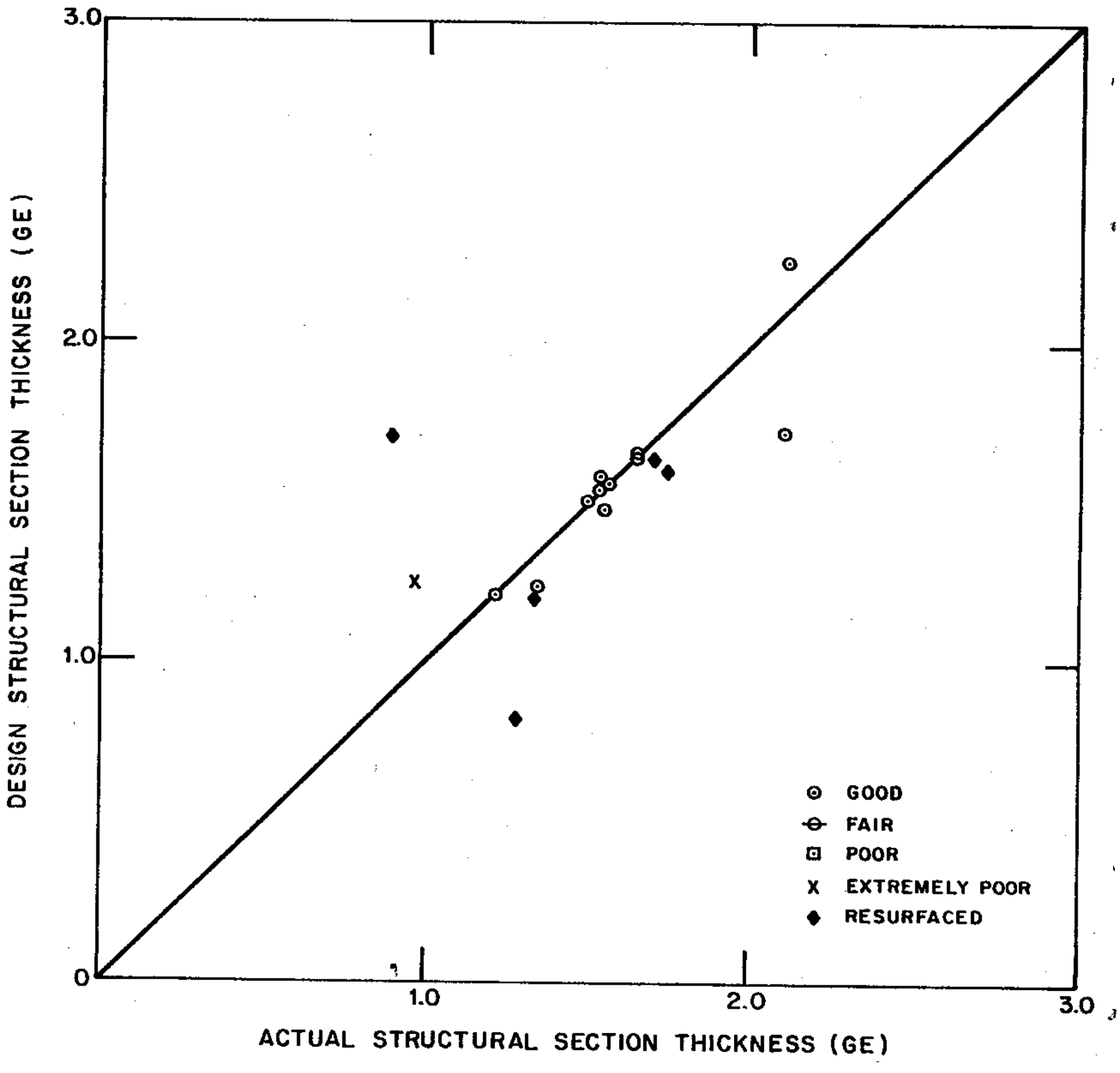
PERFORMANCE EVALUATION OF ROADWAYS INCORPORATING LIME TREATED AGGREGATES AS A BASE



* .08 blanket just meets design
** Measurements at the time the road was cored indicated that several blankets have been added (.5-.6 measured)

Figure 5

DEVIATION FROM STRUCTURAL SECTION DESIGN THICKNESS AND THE EFFECT ON PAVEMENT PERFORMANCE (LIME TREATED AGGREGATE BASE)



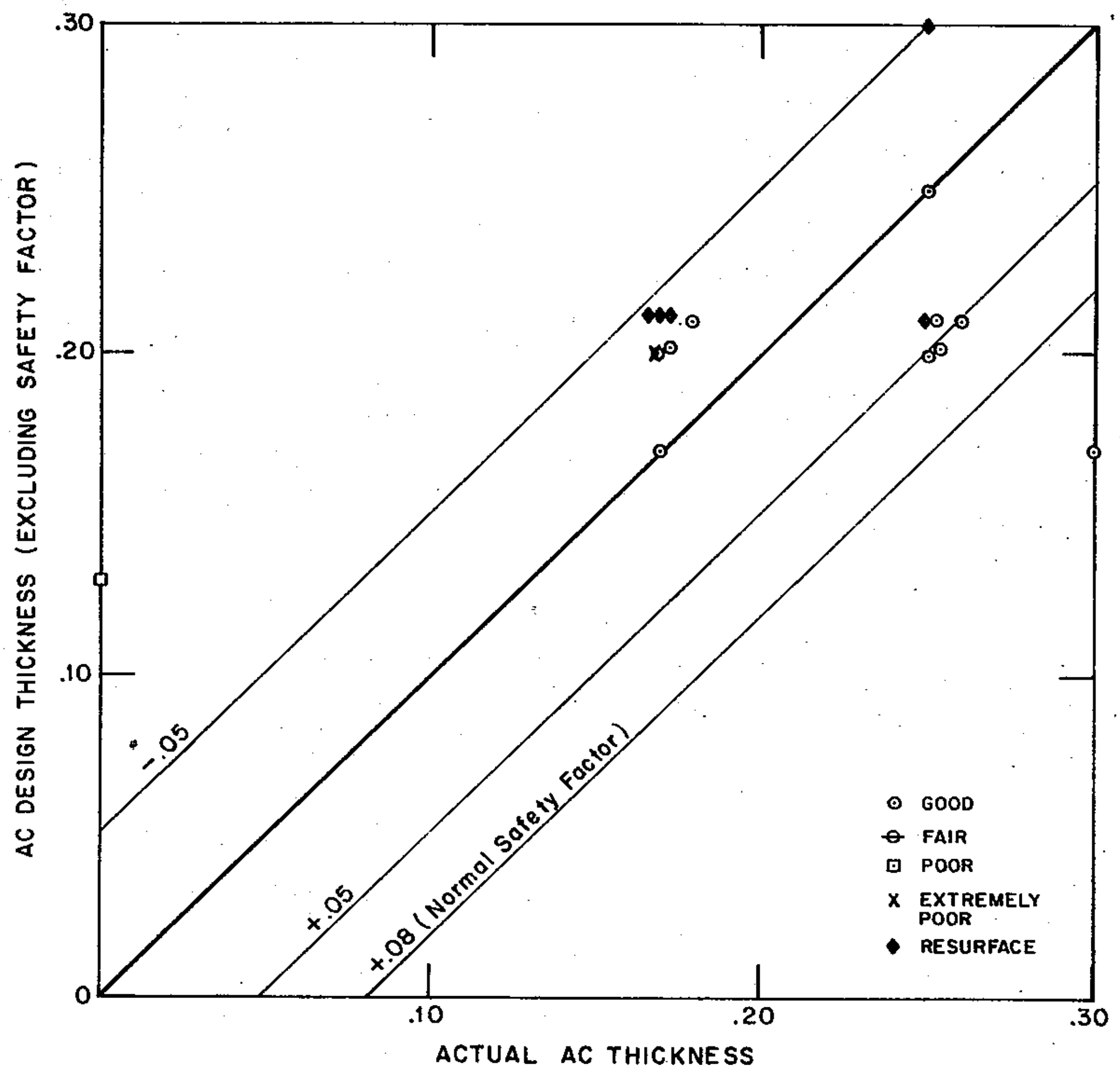
A comparison of the design asphalt concrete thicknesses with the as-built thicknesses is presented in Figure 6. Approximately one half of the projects were constructed with less than the minimum thickness of asphalt concrete indicated by the design formula. The road which was judged to be in extremely poor condition after nine years and one of the two roads which were resurfaced because of surfacing distress were deficient in asphalt concrete thickness. All of the roads except one were deficient in asphalt concrete thickness, by at least a small margin, when the safety factor requirement is considered.

Only one of the projects in this group was cored for a detailed evaluation of the in-place materials. The results of this evaluation are contained in Appendix B. It was surmised that most of the distress observed on this project was caused by lime treatment of a nonresponsive soil. Comments are also offered on two other projects where additional explanation is of importance in evaluating the performance of lime treated materials.

It was concluded from the foregoing data presentation and the information included in Appendix B that low quality aggregates which contain responsive fines can be improved by the addition of lime so as to provide a satisfactory base material for highway construction.

Figure 6

DEVIATION FROM ASPHALT SURFACING DESIGN THICKNESS
AND THE EFFECT ON PAVEMENT PERFORMANCE
(LIME TREATED AGGREGATE BASE)



Lime Treated Soil Base

The design data and structural section thicknesses for this group of roads are tabulated in Table 5. A summary of the lime treated material used on each project and an evaluation of the actual or projected surface condition of the roadway after 10 years of service are listed in Table 6. The surface conditions after various lengths of time in service, along with the length of service time prior to resurfacing, reconstruction, or coring are presented in Figure 7.

Of the thirty-five roads constructed with lime treated native soils as a base, twenty-two (63%) were judged to be in fair to good condition by the end of the ten year service period. Two other roads, although resurfaced prior to the end of the 10 year service life, were considered to have performed satisfactorily with the additional thickness of asphalt concrete being added as preventive maintenance on slightly distressed pavement. If these two are included in the number of roads rated as fair to good, the total in this classification is increased to 69 percent. The remainder were in poor or extremely poor condition or had been resurfaced as a result of major distress.

It is interesting to note that nearly all of the roads which performed poorly had been judged to be in poor or extremely poor condition when first reviewed after only a few years of service. This observation indicates that structural deficiencies in lime treated bases result in an almost immediate distress of the road. It is only logical that this would occur since there is such an extreme difference in the structural quality (R-value) between untreated and adequately stabilized soils. On the other hand, it is not unusual on other types of roads to observe good performance for a number of years, then witness a rapid rate of deterioration. These conditions may make prediction of remaining service life difficult.

Basement soil data were not available for more than half of these projects. In some cases, a minimum quality 5 R-value was assumed by the designing agency. In other instances, a 5 R-value was assumed by the researcher. Traffic Indexes were also assumed for many of these roads. In all probability, very few of these roads were actually designed on the basis of traffic surveys and basement soil stability test values. Many county roads are constructed with basic typical structural sections which have proven satisfactory previously. Others are built simply according to the structural sections which can be constructed with available funds. For these reasons, many of the roads are deficient in asphalt concrete thickness and, in fact, several have only a seal coat surface.

It was necessary to assume specific values for these unknown traffic and soil stability factors so that there could be some continuity in the method of data presentation.

A comparison of the required and actual structural thicknesses in Table 5 indicates that 26 (75%) of the 35 structural sections were deficient in total gravel equivalent thickness by more than 0.1 foot. If each of the roadways with an assumed R-value of 5 for the native soil had an actual R-value of 30, 50% of the roads in this group would still be deficient in total gravel equivalence.

In addition, approximately half of the projects reviewed were paved with less asphalt concrete surfacing than required by the design formula. By the end of the 10 year service period, only a few had been brought up to design standards by either planned stage construction or necessary maintenance resurfacing. When these structural deficiencies are taken into consideration, it is quite encouraging that as many as 63% were still in fair to good condition after ten years.

Table 5

Design of Roadways Incorporating Lime Treated Soil as a Base

Project	Agency	Traffic Index	R-value Basement Soil	Thickness Required by Design: Surface GE	Thickness Required by Design: Surface Actual	Thickness Required by Design: Total GE	As Built Structural Section: Surface Stage 1	As Built Structural Section: Surface Stage 2	As Built Structural Section: LTB	As Built Structural Section: Subbase	As Built Structural Section: Total GE
BS1	County	5(a)	5(a)	0.38	0.16	1.50	0.17		0.50		0.99
BS2	County	6.0	5(a)	0.38	0.16	1.82	0.21		1.13		1.84
BS3	County	7.0	11	0.45	0.21	1.98	0.15 RMAS		0.50	0.50 LTS	1.69
BS4	County	5(a)	5(a)	0.35	0.14	1.50	0.13		0.67		1.14
BS5	County	7.2(a)	17(a)	0.45	0.21	1.90	0.08	0.12	0.67		1.23
BS6	County	6.0	5	0.38	0.16	1.80	0.33 RMAS		1.00		1.60
BS7	County	7.0	11	0.45	0.21	2.00	0.08		0.83		1.17
BS8	County	7.0	5-13	0.45	0.21	2.12	0.25		1.00		1.17
BS9	County	6.0	5(a)	0.38	0.16	1.82	0.17		1.00		1.60
BS10	County	7.0	7	0.45	0.21	2.10	0.25		1.00		1.74
BS11	County	6.0(a)	5(a)	0.38	0.16	1.82	0.12		0.67		1.10
BS12	County	6.0(a)	16	0.38	0.16	1.60	0.08		0.67		1.00
BS13	County	6.5	5(a)	0.42	0.20	1.98	0.25		0.50	0.75 LTS	2.00
BS14	County	6.5	5(a)	0.42	0.20	1.98	0.17		0.50	0.75 LTS	1.86
BS15	County	7.0	5(a)	0.45	0.21	2.12	0.17		0.50		0.94
BS16	County	5	5	0.35	0.14	1.50	0.17		0.83		1.40
BS17	FAS	7.5	5(a)	0.47	0.23	2.27	0.17	0.17	1.25		2.18
BS18	FAS	7.5	5(a)	0.47	0.23	2.27	0.17	0.17	1.25		2.18
BS19	County	7.0	5(a)	0.45	0.21	2.12	0.25		1.08		1.84
BS20	County	7.0	5(a)	0.45	0.21	2.12	0.25		1.08		1.84
BS21	County	<5	5(a)	0.35	0.14	1.50	0.12 RMAS		0.50		0.84
BS22	County	6.0	5(a)	0.38	0.16	1.82	0.13 RMAS		0.50	0.50 LTS	1.44
BS23	County	5.0	5(a)	0.32	0.13	1.50	0.13 RMAS		0.50		0.74
BS24	County	6.0	5(a)	0.38	0.16	1.82	0.13 RMAS		0.50	0.50 LTS	1.44
BS25	County	7.0	26	0.45	0.21	1.65	0.20		0.50		1.03
BS26	County	6(a)	67	0.38	0.16	0.63	0.12		0.67		1.10
BS27	County	5(a)	31	0.32	0.13	1.10	Seal Coat		1.00		1.20
BS28	County	5(a)	20	0.32	0.13	1.30	Seal Coat		0.75		0.90
BS29	County	5.5	5(a)	0.35	0.15	1.67	0.13 RMAS		0.50	0.50 LTS	1.36
BS30	County	4.5	5	0.28	0.11	1.35	0.17 RMAS		0.40	0.40 LTS	1.16
BS31	County	6.0	8	0.38	0.16	1.75	0.17		0.83		1.39
BS32	County	6(a)	5(a)	0.38	0.16	1.82	0.08		0.83		1.20
BS33	County	6(a)	28	0.38	0.16	1.38	0.08		0.83		1.20
BS34	County	4.5	9	0.28	0.11	1.30	Chip Seal		0.67		0.80
BS35	County	5	15	0.32	0.13	1.35	0.20		0.67		1.30

GE = gravel equivalent
AC = asphalt concrete
RMAS = road-mixed asphalt surfacing
AB = aggregate base
AS = aggregate subbase

LTB = lime treated base
LTS = lime treated subbase
IB = imported base
(a) = assumed

Table 6

Materials and Surface Condition Information for Roadways Constructed with Lime Treated Soil as a Base

	Material Treated				Surface Condition Survey						
			Lab R-value		Cracking				Pothole	Overall*	Years'**
Project	Type	% Lime	Before	After	Longt.	Trans.	Allig.	Rutting	or Patch	Condit.	Service (If other than 10)
BS1	Soil	4								Good	9
BS2	Soil	4			✓		✓	✓	✓	Fair	–
BS3	Soil	3(2 in LTS)	11–17	80			✓	✓	✓	Poor	–
BS4	Soil and Exist Gravel	5	No tests		✓	✓				Good	–
BS5	Soil	4	17	85						Good	–
BS6	Soil	5					✓	✓	✓	Extremely Poor	6
BS7	Soil and Exist Gravel	3.5		80	✓	✓	✓		✓	Fair	–
BS8	Soil and Exist Gravel	4.6 (S)	5+							Good	–
BS9	Soil	5		81	✓	✓	✓	✓		Good	–
BS10	Soil	3	7–14	69–90						Good	9
BS11	Soil	4					✓	✓		Good	9
BS12	Soil	4			✓	✓	✓			Fair	9
BS13	Soil	4 (S)		79–82			✓		✓	Fair	–
BS14	Soil and Agg. Base	4 (S)		79–82			✓		✓	Extremely Poor	9
BS15	Soil	4		79–81			✓		✓	Extremely Poor	4
BS16	Soil and Exist Gravel	2	5–28	80+	✓					Fair	–
BS17	Soil and Exist Gravel	4	3+	74–81			✓		✓	Good	–
BS18	Soil and Exist Gravel	4	3+	74–81			✓		✓	Good	–
BS19	Soil	6 (top) 4.5 (bottom)		80	✓		✓		✓	Good	–
BS20	Soil	6 (top 4.5 (bottom)		80	✓		✓		✓	Good	–
BS21	Soil	4					✓		✓	Poor	–
BS22	Soil	3 (top) 2 (bottom)					✓	✓	✓	Poor	–
BS23	Soil	4							✓	Good	–
BS24	Soil	3 (top) 2 (bottom)								Good	–
BS25	Soil	4					✓			Poor	–
BS26	Soil	4			✓	✓	✓	✓	✓	Fair	8
BS27	Soil	3–5	31	85–90	✓		✓	✓		Fair	–
BS28	Soil	3.5	20	68–90					✓	Poor	8
BS29	Soil	4 (top) 3 (bottom)					✓	✓	✓	Extremely Poor	2
BS30	Soil	4 (top) 3 (bottom)								Fair	9
BS31	Soil	3	29	82						Fair	7
BS32	Soil	3	10–16		✓	✓				Good	–
BS33	Soil	3	28		✓	✓				Good	–
BS34	Soil	3	9–23	59					✓	Extremely Poor	3
BS35	D.G. & Clay	2 (Q)	13–30	80–91	✓					Good	7

(S) = sludge lime

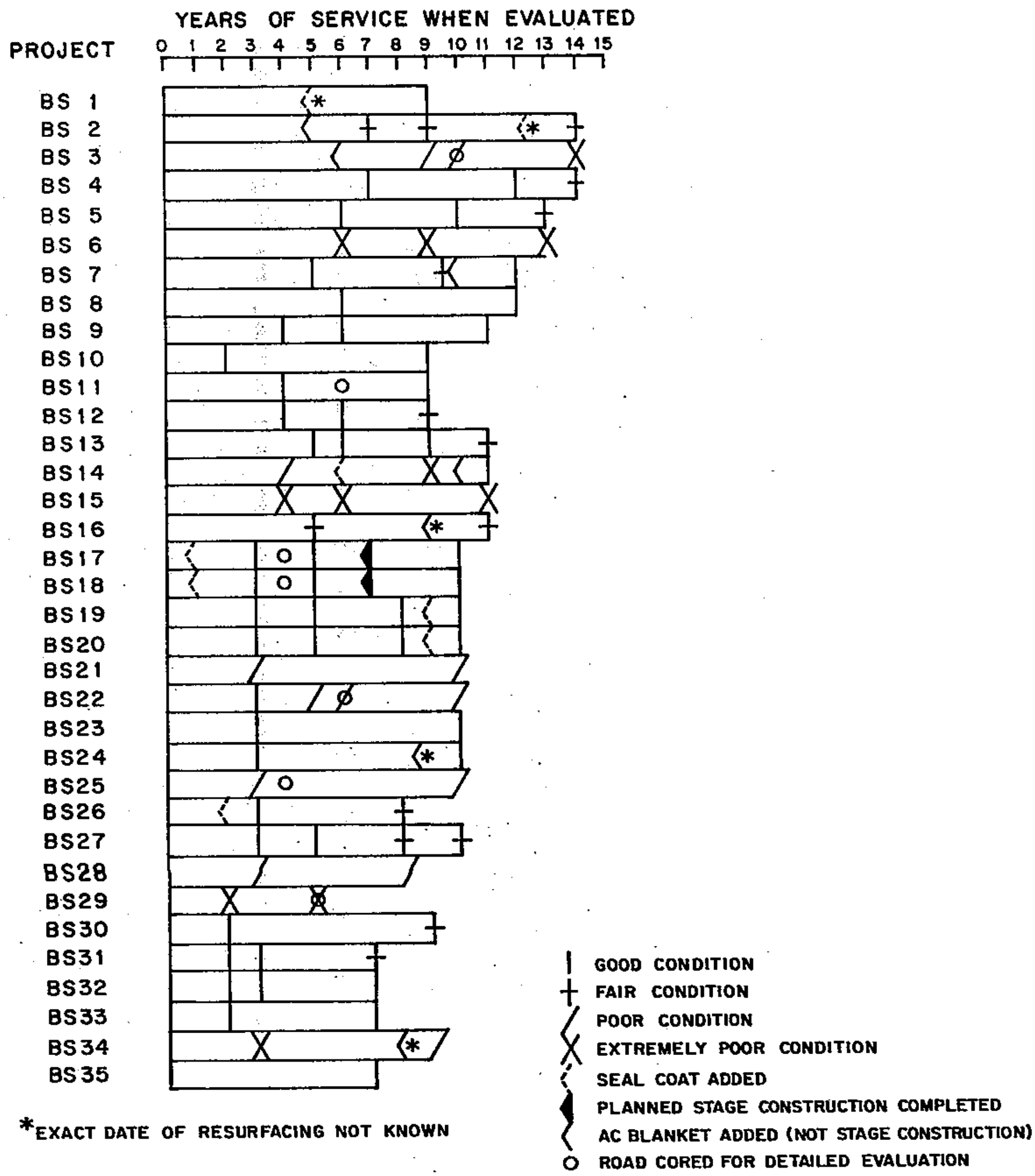
(Q) = quicklime

*Actual or interpolated condition at end of 10 year service.

**Actual years of service if less than 10 at the end of the study, or if more than 10 when initial survey was made. The years of service prior to a rating of "extremely poor" are noted even though the road may have been reviewed at a later date.

Figure 7

PERFORMANCE EVALUATION OF ROADWAYS INCORPORATING LIME TREATED SOILS AS A BASE



Comparisons of the required (by design criteria) and actual total gravel equivalent thickness and asphalt concrete surfacing thicknesses are presented in Figure 8 and 9 respectively. Based on Figure 8, there is little correlation between road performance and deficiency of the gravel equivalence of the total structural section. Many roads were found to be in good condition even though deficient by up to 0.75 foot in gravel equivalence. Others had been resurfaced or were in various stages of distress even though the constructed section was adequate or only slightly deficient according to the design formula.

Figure 9, however, indicates once again that there is a correlation between performance and deficiency in the asphalt concrete thickness. Eighty percent of the roads which were constructed with asphalt concrete surfacing equal to or exceeding the design requirement were in fair to good condition after 10 years. Fifty-five percent of the roads which were deficient by no more than .05 ft. were in fair to good condition while only 45 percent of the roads which were deficient by more than .05 ft. remained in fair to good condition.

Seven roads from this group were selected for coring and detailed evaluations of the in-place materials. Projects BS3, BS22, BS25 and BS29 were selected for this phase of the study because of the widespread distress they contained. Projects BS11, BS17 and BS18 were selected because of their good condition even though there was occasional isolated distressed areas.

The observations and findings of these detailed investigations are summarized in Appendix C. It was concluded that major contributors to the observed distress were treatment of non-responsive material, poor lime distribution uniformity, and deficiencies in the constructed thickness of the LTB or AC.

Figure 8

DEVIATION FROM STRUCTURAL SECTION DESIGN THICKNESS AND THE EFFECT ON PAVEMENT PERFORMANCE (LIME TREATED SOIL BASE)

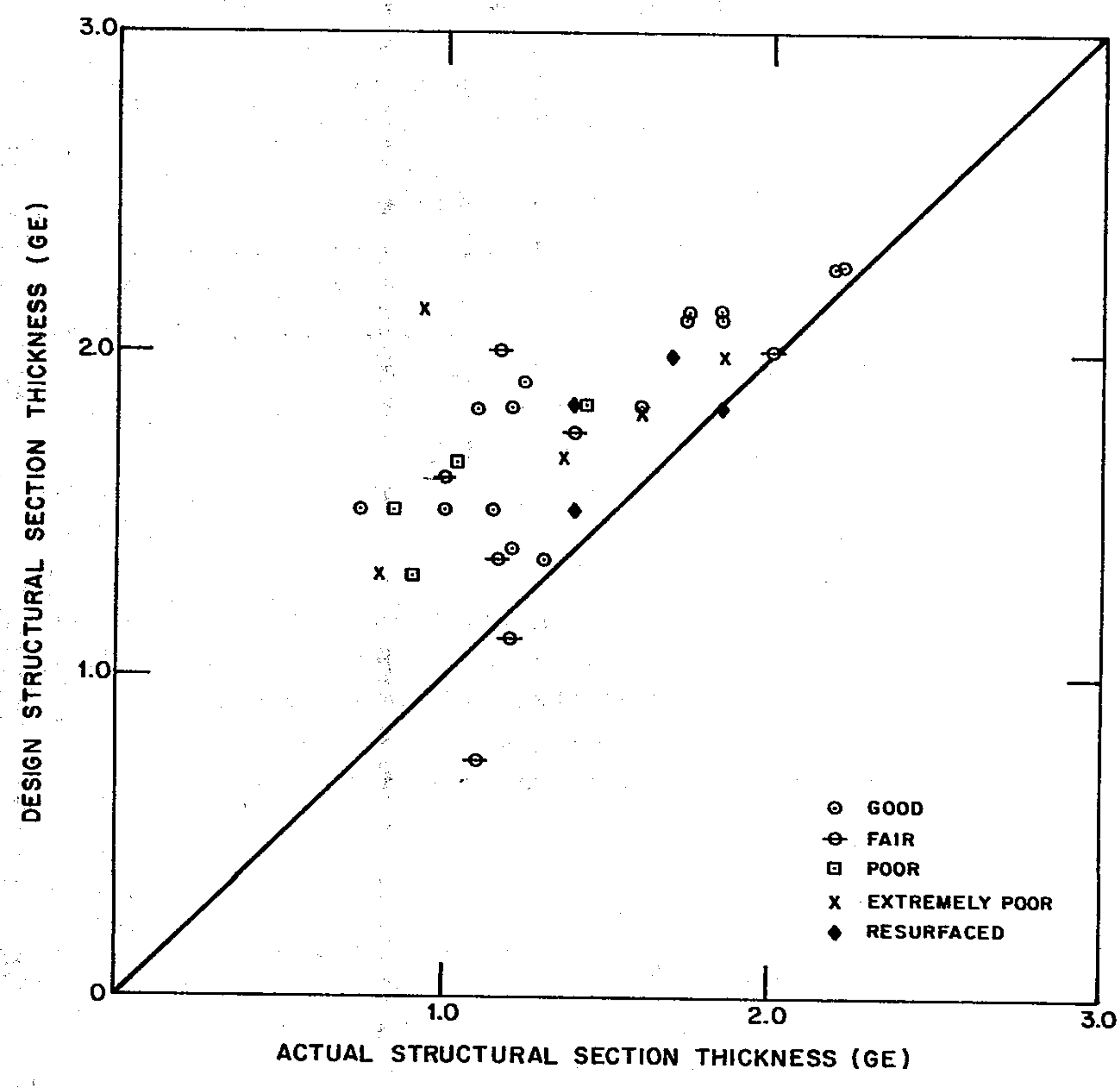
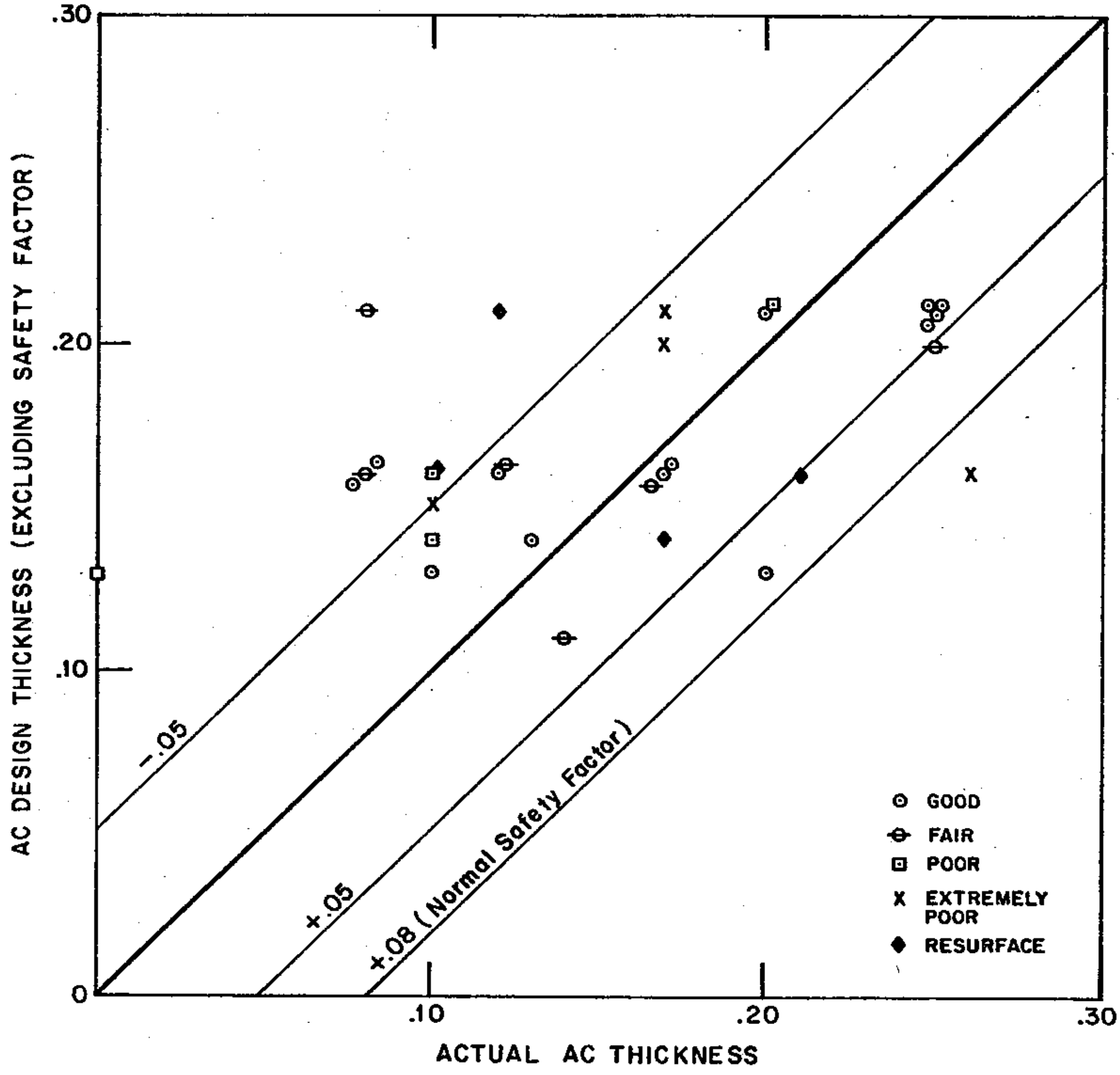


Figure 9

DEVIATION FROM ASPHALT SURFACING DESIGN THICKNESS AND THE EFFECT ON PAVEMENT PERFORMANCE (LIME TREATED SOIL BASE)



Although not included in the group of roads selected for coring, pertinent information is available for several other roads which offer significant insight into their performance. Project BS2, for example, began to show evidence of distress shortly after construction. An investigation by the county revealed inadequate mixing of the lime treated material. Some locations, in fact, were found to be completely void of lime. Project BS14 almost satisfied the design criteria yet it was in poor condition by the time it was in service four years. This section of road was a main thoroughfare in a developing area and, as a result, carried high volumes of truck traffic, particularly ready-mix concrete trucks, for street, home, and shopping facility construction.

DISCUSSION OF PERTINENT FACTS AND OBSERVATIONS

During the field evaluations, sampling and testing of in-place materials, and discussions with materials and construction engineers in various agencies, many pertinent facts and observations were brought to light. Those which are of importance in the design or construction of lime treated roadways are as follows:

Variations in Lime Type

Some of the early lime treatment projects were constructed using commerically available "hydrated lime" or "agricultural lime". No quality specifications were placed on the lime prior to 1959 but it can be assumed, from later experience with various limes, that the calcium hydroxide [$CA(OH)_2$] content has normally been in excess of 75 percent. Beginning in 1959, the State of California has set minimum calcium hydroxide requirements on all lime used for soil stabilization on projects under its control. As far as is known, cities and counties within California have generally followed the States' recommended specifications. Records indicate that the minimum calcium hydroxide content of lime products used on projects included in this study has varied from 75 to 90 percent.

Several projects were constructed using sludge lime, which is obtained as a by-product when acetylene gas is produced from calcium carbide. This type of lime normally had a relatively high calcium hydroxide content but is at times variable in quality and in the amount of free water present.

A substantial number of projects in a few counties were constructed with quicklime in lieu of hydrated lime. Because quicklime's chemical affinity for water has not been satisfied, the rapid sugar method of determining calcium hydroxide content indicates a much higher relative calcium hydroxide content than for hydrated lime. By this test method, which is used in California to evaluate the quality of lime, a quicklime of the same purity as a hydrated lime with 85 percent calcium hydroxide would have an indicated calcium hydroxide content of approximately 113 percent.

Information accumulated during this study failed to show that roads constructed with any one type of lime are more durable than roads constructed with any other type of lime. However, various draw-backs or advantages were noted by individuals directly involved with the use of lime which could affect road performance.

As mentioned in the following section on Construction Methods and Equipment, the finely ground hydrated limes tend to be difficult to discharge uniformly from distribution equipment. In addition, dust is often a matter of considerable concern during both the distribution and mixing of these products. There have, in fact, been occasions when construction has been shut down because of the amount of lime dust in the air.

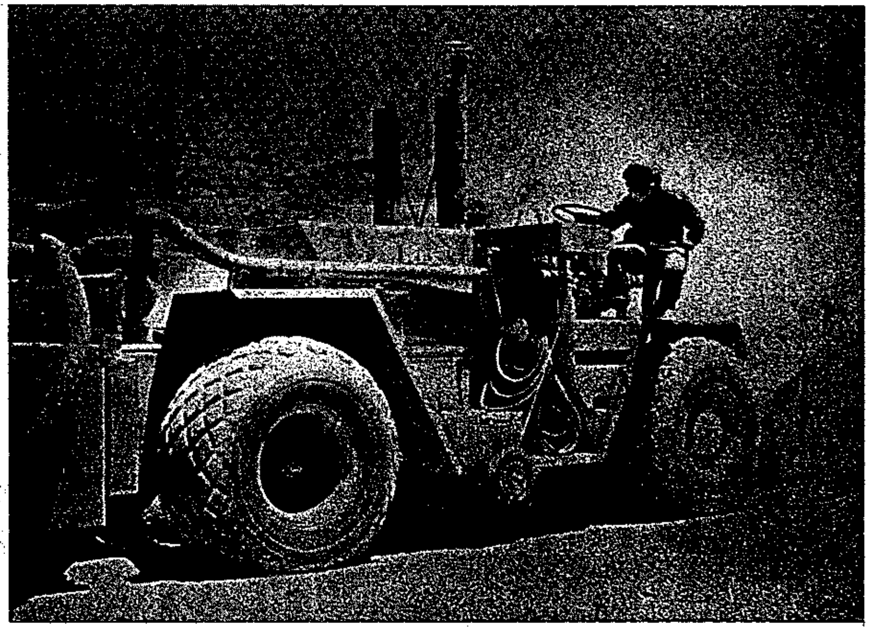


Figure 10
Dust Problem with Finely Ground Lime

Prior to 1975, the California specifications for lime treatment required that if more than one pass of the mixing equipment was necessary, then at least one pass was to be made before mixing water was added. This also often resulted in an extremely dusty operation. At the same time, the specifications have usually allowed adding water to the lime after distribution to prevent blowing. This is accomplished by sprinkling with a water truck. On two of the projects included in this study, balls of lime putty up to 3/8-inch or more in size were found during the detailed investigations. In both cases, it was determined that water had been sprinkled on the distributed hydrated lime to prevent blowing and as a result the lumps were formed. The formation of these lumps was documented in the Resident Engineer's final report on one of the projects. According to the Resident Engineer's statement, the lime balls were formed as a result of the sprinkling operation and were not broken up in the mixing operation. Representatives of the lime company assured the engineer that these balls would dissolve in time and that the lime would migrate throughout the base material. The lime balls were still evident, however, in cores taken ten years after construction.

The problems of distribution and dust are both greatly reduced when granular quicklimes are used. Quicklime also provides an economical advantage in that the water for hydration, which amounts to over 25 % of the weight of hydrated lime, is added at the job site. There are, however, some precautions to be considered when using quicklime. Because of quicklime's chemical affinity for water and the high temperatures developed during the hydration process, there is some danger involved. Rapid flooding of confined quantities of quicklime should be avoided and personnel should protect themselves from direct contact with the quicklime as much as possible. Severe burns can be caused by quicklime coming in contact with water or perspiration on the body. The eyes, nose and mouth are especially vulnerable to burns from quicklime.

Sludge lime is normally available in a wet condition. The amount of free water in this product may vary considerably, thus creating new problems in uniformly distributing the lime. Allowances must be made for nonuniform moisture content and a different type distributor is required. For example, some agencies which have used sludge lime have made use of agricultural manure spreaders for distributing the wet lime.

It is concluded that the type of lime is not critical to the soil stabilization process provided the necessary calcium oxide can be uniformly blended with the soil. Safety, environmental considerations, capabilities of spreading and mixing equipment, and economics are important factors, however, which must be considered when choosing between various types of available lime.

Inadequate Lime Distribution

The road condition survey revealed that some pavement distress, in the form of alligator cracking or rutting, was present to some extent in more than 50 percent of the lime treated base projects. In the majority of these cases, the cracking and rutting was limited to a few localized areas of the total project indicating the probability of some variations in the structural section. Subsequent detailed investigations of individual projects, along with supplemental background information from the responsible agencies, confirmed that nonuniform distribution of the lime was directly responsible for many of the localized failures.

As discussed in the detailed investigation review, Project BS2 began to show evidence of distress shortly after construction. An investigation by the county revealed inadequate distribution of the lime with some locations being completely void of lime.

Core samples and test holes revealed areas of poor lime distribution in Projects S6, BA7, BS11, BS17 and BS18. It was concluded that this poor distribution was a primary reason for the distress observed on each of these projects. There were indications that this was also true on several other projects but the evidence was not conclusive because of other contributing factors.

A major portion of the observed deficiencies in lime distribution was probably the result of inadequate equipment and/or inexperience of the contractor as well as the contracting agency. As equipment and experience have improved over the past several years, the problems of nonuniform distribution of the lime have been greatly reduced. The following section on Construction Methods and Equipment offers additional information on the types of equipment available and some of the problems that have been encountered.

Construction Methods and Equipment

During the early stages of the use of lime stabilized materials, the lime was distributed by depositing bagged lime at calculated intervals. Mixing was then accomplished with farm discs or motor graders (see Figure 11). Neither of these methods provided really reliable mixing, especially in the heavy clay materials. It was also difficult to maintain a uniform mixing depth with the disc. These same problems were encountered in early soil-cement projects in the midwest.

Bulk lime soon replaced the bagged lime but uniform distribution over the roadway or in a windrow proved to be a difficult problem. Cement distributor trucks, bottom dump trucks with drag type spreader boxes, and screw fed vane type distributor hoppers were tried, but great difficulty in applying the lime at a uniform rate was experienced with all of them. The finely ground lime bridged the openings and would not flow at all or flowed so freely that it could not be controlled. On one job, workmen were required to walk along side the bottom dump transport trucks and pound the sides with rubber mallets while another man poked the lime down from the top using a long rod (see Figure 12.)

Figure 11
Mixing Lime and Soil With Farm Disc.

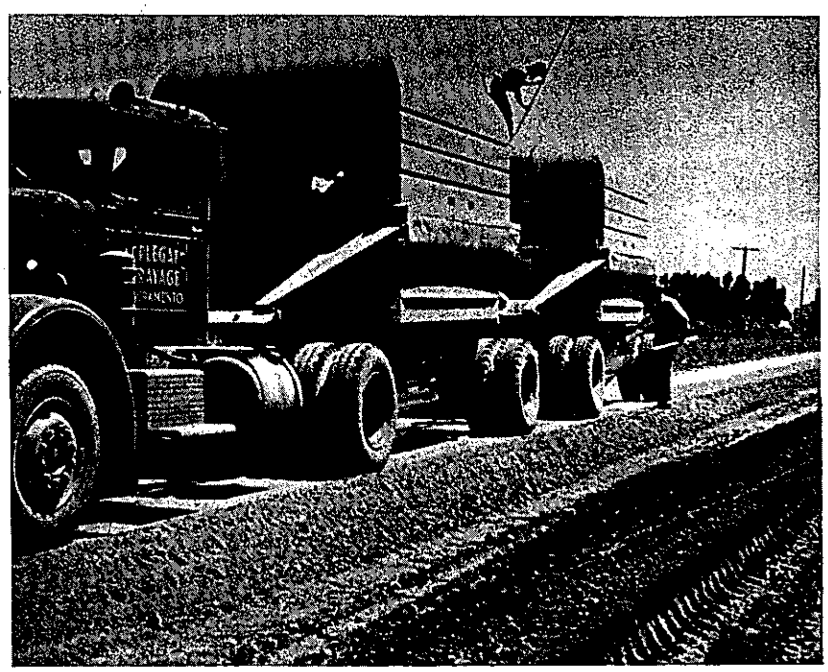


Figure 12
Assisting Lime Discharge From Transport - Distributor

As the use of lime increased, most of the work was taken by specialized contractors and specially designed spreading equipment was developed (see Figure 13). Vibrators and circulation systems built into the spreaders helped alleviate much of the difficulty in distributing the bulk lime. With the increase in acceptability of granular quicklimes during the past few years, the problem of distribution has been reduced even further. Some agencies have found that the uniformly graded granular quicklimes can be spread with sufficient uniformity by tailgating from an end dump truck.

Pug mill type mixers (see Figure 14) were found to be satisfactory for mixing loose granular materials but they were totally useless for mixing heavy clay materials. In some instances the soils built up on the paddles and in the drum of the pug mill until it was completely clogged. Tractor mounted, cross shaft, rototiller type mixers (see Figure 15) soon proved their effectiveness in mixing lime with the finer grained materials, including heavy gumbo clays. The smaller farm type tillers were sometimes incapable of maintaining uniform depth control but several manufacturers have developed large towed or self-propelled mixers which are very effective for mixing lime with the soil and at the same time adding controlled amounts of water. Problems with depth control have also been virtually eliminated.

It is concluded that the equipment and procedures currently used by experienced contractors have greatly decreased the chances of road failures due to inadequate distribution and mixing of the lime.

Figure 13
Distributor Truck With Vibrator and Recirculation System

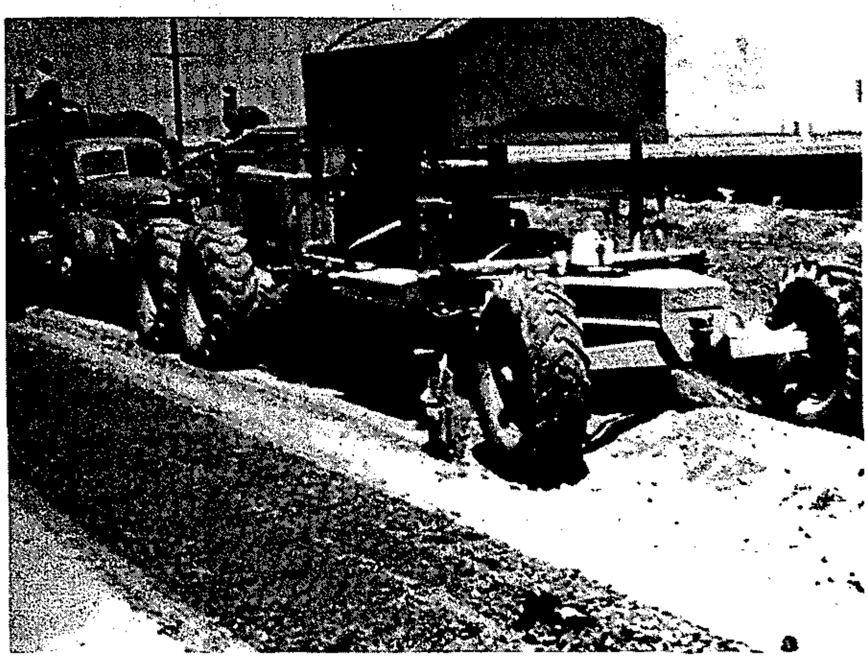


Figure 14
Pug Mill Type Mixer

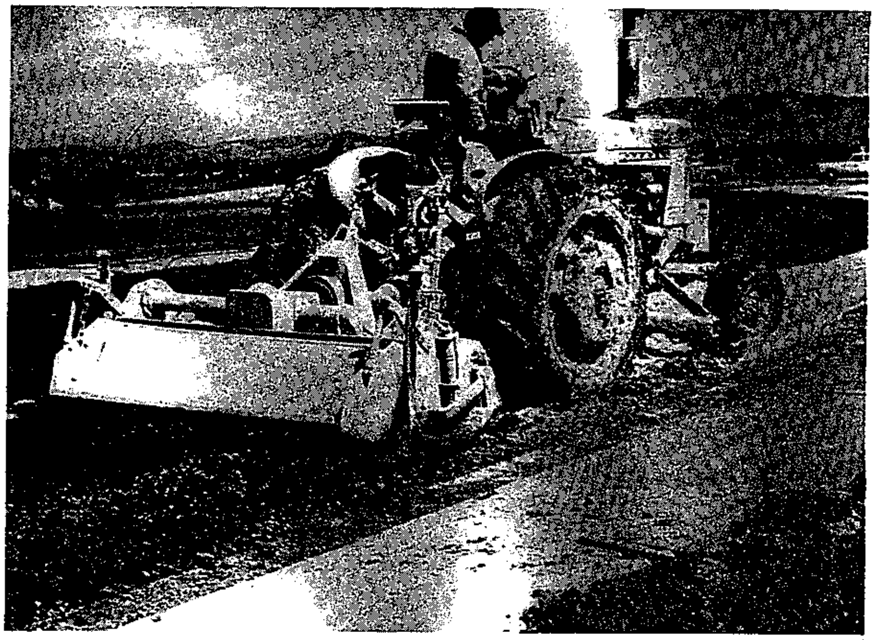


Figure 15
Tractor Mounted Rototiller

Stratification of Lime Treated Material

During the coring and sampling phase of this study, it was observed that the lime treated material on several projects separated into layers. In some cases, these layers were obviously different materials, often alternating between well-cemented and poorly cemented. In other cases, each of the layers was well cemented but there was little or no bond between layers.

It is concluded that much of the stratification of the lime treated material was the result of mixing the lime in thin layers. On several projects where the lime treated material was known to have been mixed and compacted as a series of thin layers, the core samples separated accordingly (see Figure 16). On other projects where the treated material was placed in six inch layers because of thickness limit specifications, the core samples tended to separate on these compaction planes. At one test site, the top 0.1 ± ft. of lime treated material separated from the rest of the layer on a smooth textured, corrugated surface. Both portions were well cemented and it was very obvious that the separation was on a plane left by construction equipment.

This separation on compaction planes has also been observed in laboratory compacted test specimens. One load application of the kneading compactor as the test material is being built up in the compaction mold is often enough to create a poorly bonded compaction plane (see Figure 17).

There is insufficient data to estimate how much the strength of a well cemented lime treated material would be reduced by the lack of bonding between layers. It is certain, however, that the load carrying capacity of the road would depend directly on the strength and position of the poorest quality lime treated material in a nonuniform layer. Also, the lack of composite action by the subbase or base will decrease the load carrying capacity of the structural section to some degree. For these reasons it is recommended that the maximum lift thickness for lime treated soils be increased to 12 inches and that a minimum lift thickness of 4 inches be added to the specifications. Uniform distribution of the lime and adequate compaction are essential, however, and authorization to mix and compact thicknesses greater than 6 inches should be subject to the judgement of the Engineer and the contractor's ability to comply with all the other specification requirements.

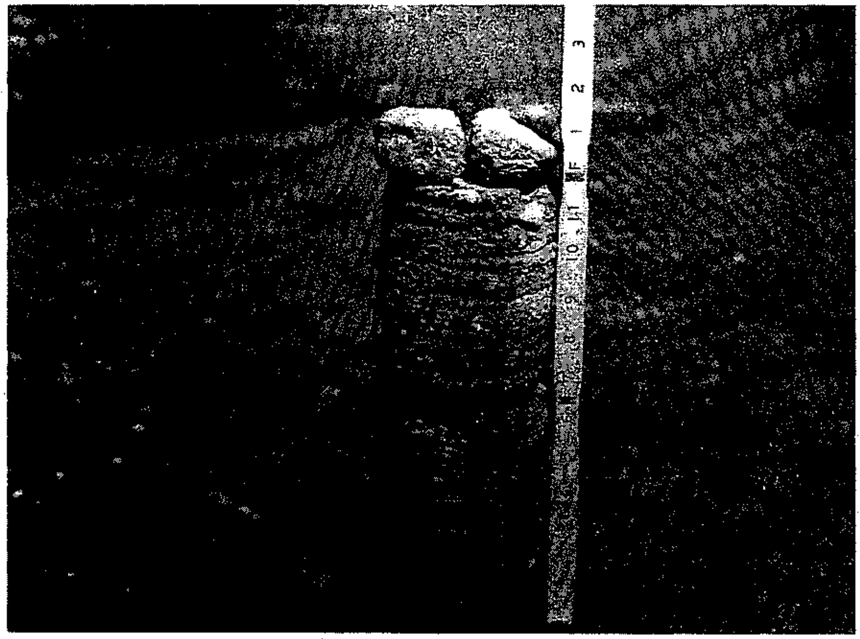


Figure 16
Construction Planes in Lime Treated Soil

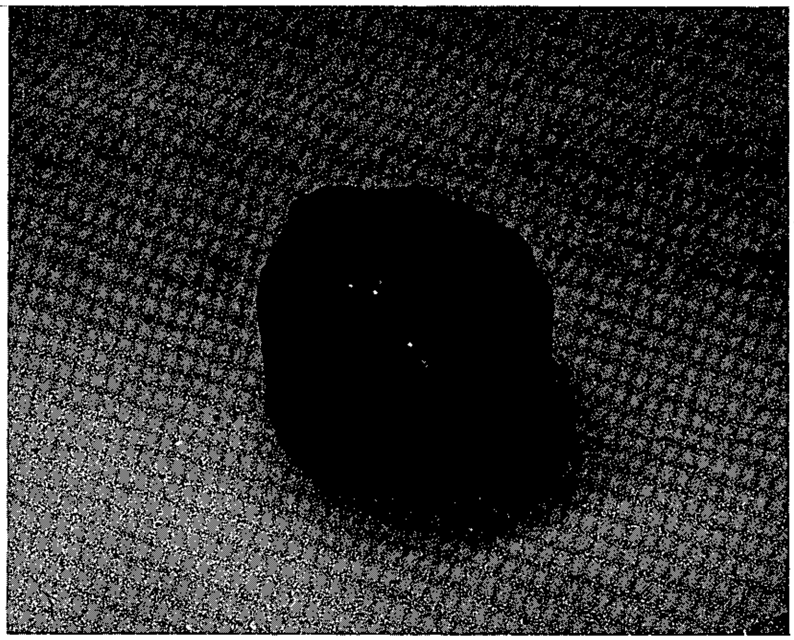


Figure 17
Compaction Planes in Laboratory Test Specimen

Nonresponsive Materials

During the course of the field review, and while discussing the use of lime treated soil with various county materials engineers, several instances were brought to light where major distress had developed within a very short period of time after construction. This occasionally occurred even though design and construction procedures and equipment appeared adequate. In these cases, preliminary laboratory tests indicated that lime could be used to effectively improve the structural quality of the soils but when the lime was used in construction the treated material failed to provide the necessary load bearing capability. Situations like this have given rise to speculation that the reaction between lime and at least some soils may be reversible. It has certainly had an adverse influence on decisions to use lime stablized soils in some areas.

One very good example was a county road in the central San Joaquin Valley where extensive pavement distress developed within the first year following construction. Preliminary tests had indicated that material suitable for use as a substitute for aggregate base could be provided by lime treating the native soils. In the laboratory, only 2% quicklime was required to raise the R-value from less than 10 to 75 or above. Based on these preliminary tests, the road was designed and constructed using a structural section consisting of 0.15' AC, 0.50' LTB and 0.60' LTS. The LTB and LTS both consisted of lime treated native soils.

When pavement distress became obvious after the first winter, the county cored and sampled the structural section at several locations. Very little slab strength was observed and laboratory tests on the recovered materials indicated R-values for the treated soils from 34 to 76 with an average R-value of less than 50. Preliminary R-value tests and R-value tests of materials sampled from the road immediately after mixing with lime, both indicated that the native soils would react favorably with lime. It can be assumed then that a similar R-value was achieved initially in the roadway, but the reaction was not permanent.

Two other projects in the same general area developed similar distress. One of these was constructed in 1966 with a structural section consisting of 0.13' RMAS, 0.50' LTB, and 0.50' LTS. Once again, the LTB and LTS both consisted of lime treated native soils. Four percent hydrated lime was specified for the LTB and 3 percent for the LTS. When reviewed after two years of service, there were numerous patched and failed areas throughout the length of the 2 mile project. The failures were in the form of alligator cracking and rutting. The rutting was generally accompanied by a heaving at the edge of the pavement. Five years after construction, this structural section was cored and sampled at two locations as a part of this study. Laboratory tests showed R-values of 23 and 29 for the LTB and 9 and 14 for the LTS. Again assuming that the planned amounts of lime had actually been added at these locations, it appears that the soil either did not react with lime or the reaction was not permanent.

Similar circumstances have also been observed in other geographic locations. Another county near the coast of northern California experienced the same type of early distress in two large parking lots which had been constructed with 0.12' AC over 0.50' of native soil treated with 4% lime. Preliminary tests indicated that R-values of 80 or above could be expected. Pavement failures developed within a very short period of time. When the in-place materials were resampled, they were soft and friable with no apparent cementing. Laboratory tests revealed R-values as low as 26 in lieu of the anticipated 80.

Another roadway in southern California developed extensive distress shortly after construction. The original structural section design consisted of 3-1/2" AC, 6" CTB, and 6" AB to provide adequate cover for the 5 R-value basement soil. During construction, high field moistures and a soft yielding subgrade were encountered. To remedy the situation, the structural section was modified to include a 1 ft. thick layer of lime treated basement soil. Laboratory tests indicated that adding 4% hydrated lime to the soil would increase the R-value to 50 and above. When the road started to fail, the in-place materials were resampled and tested. Instead of a 50+ R-value LTS, it was found that R-values were as low as 25. This in itself should not have caused the extensive distress observed in the pavement but further laboratory tests indicated that the soil still had extreme expansive characteristics even after being treated with up to 20% quicklime.

There have been other instances where the structural quality of a lime treated material has apparently diminished with time but sufficient data are not available for documentation.

A partial chemical analysis and an estimation of the minerals present in the soils from each of the 5 projects mentioned above has been summarized in the table on the following page.

Other researchers (5,6) have reported that both sulfates and organic matter can render a soil unsuitable for stabilization with cement, lime, or lime-ash mixtures. The data listed in the above table shows that the soils from each of the mentioned projects contained either sulfates, organic matter, or both. Gypsum, which is calcium sulfate, was found in substantial quantities in three of the soils and a lesser amount in a fourth. Up to 5 percent organic matter was also found in four of the soils.

Chemical and Mineral Content

Mineral	Percent of Total Sample				
	Soil #1	Soil #2	Soil #3	Soil #4	Soil #5
Quartz	25	20	25	25-30	20
Mixed Layer Clay	25-30	20	15		10
Montmorillonite				20	10
Gypsum	<5	10-15	10-15		10-15
Feldspar	10-15	10-15		10-15	20-25
Chlorite	5	5	5		5
Calcite	5	5	<5		
Mica	5	5	5		<5
Amphibole	5	<5	<5		<5
Iron Oxide	5	<5	5	<5	5
Serpentine	<5	<5	10-15		
Organic	<5	<5	5	5	
Exidote			10-15		
Amorphous					
Zeplite				5	
Kaolinite	10-15				
Glauconite	5				
Iron Sulfide				<5	
Vermiculite				20	

Chemical	Content				
SO_4 ppm	9,500			100	12,000
CaO %	2.1	1.64	1.04	.75	3.03
Na_2O ppm	nil	15,070	4,745	30	0
Soluable Salts ppm	32,900	40,200	19,020	450	21,800
pH	7.40	8.5	8.0	6.95	7.9

It was not within the scope of this investigation to determine which elements adversely effect the lime-soil reaction or at which stage strength was affected. The data accumulated, however, indicates that the presence of sulfates and organic matter may be responsible for at least a portion of the distress which has developed in some lime treated roadways. This possibility should be studied in greater detail with consideration being given to restricting the use of lime treatment when certain minerals or chemicals are present in the soil. Some long-term curing periods should also be examined.

Leaching of Lime

During the coring and sampling phase of this study, a thin layer of apparently untreated soil was observed on the surface of the lime treated material in several of the test holes. This thin layer varied in thickness up to .07 foot and was usually soft and pliable even though the remainder of the layer was well cemented. Despite the fact that this layer lacked the appearance of having been lime treated, chemical analyses indicated that lime was present at approximately the same ratio as the cemented portion of the treated layer.

Field reviews and discussions with county engineers revealed several similar situations where there was an apparent lack of lime in the upper portion of the layer.

On one county project, test holes were dug through the lime treated layer several days after final compaction. When phenolpthalein indicator was applied to the sides of the test holes, there was no color reaction to indicate the presence of lime in the top half-inch or so of the layer. Following final compaction of the lime treated material, the surface had been kept moist by repeatedly spraying with water until the aggregate base was added. In some areas, this amounted to several days and numerous applications of water. No apparent distress had developed in this road as a result of the described conditions; however, the potential detrimental effect was probably minimized by the layer of aggregate base. The soft clay on the surface of the LTS probably migrated and dispersed into the aggregate base layer. If the overlying layer had been more dense, such as asphalt concrete, the layer of soft clay would have been confined between two impenetrable materials and could have affected the performance of the surfacing.

On another lightly travelled county road near the coast, a thin layer of soft clayey material was observed on the surface of the lime treated soil during the field review. This road, which was designed for very light traffic, consists of a double seal coat over lime treated soil. The surface was badly cracked and contained numerous patches. The layer of soft clay was observed at locations where the surfacing had cracked or peeled away and seemed to vary in thickness up to a quarter of an inch. The treated material below this layer seemed to be firm. Whether the layer of untreated fines was the cause or the effect of the surface distress is inconclusive, but construction records revealed that no curing seal was applied to the compacted, lime treated soil and that it rained for several days immediately after the final mixing.

During discussions with the materials engineer of another central California county, it was learned that he had observed and documented the effects of water and traffic on lime treated soil. No detour was available and it was necessary to maintain traffic through the job site. Water was applied to the surface to keep the layer in a moist condition. When it was observed that the surface was remaining soft, the engineer sampled the material for laboratory tests. Testing revealed that the lower portion of the treated layer had achieved an R-value of 78 while the material taken from the soft surface material had an R-value of only 19.

The evidence noted above leads to the conclusion that repetitious watering of the surface, especially when accompanied by traffic, can have a detrimental effect on at least the upper portion of a lime treated material. This observation has also been reported by other researchers. The State of Missouri (7) reported "...At various locations a thin clay-like layer was noted at the top of the course. This was believed to have resulted from repeated applications of water while curing....". A representative of the National Lime Association has also mentioned that they have observed similar situations which they believe are due to carbonation of the lime in the exposed surface or the lime being flushed out by water application.

For these reasons, it is concluded that lime treated materials should be sealed with an asphaltic emulsion curing seal as soon as possible after final rolling and traffic should not be permitted on a finished surface before it has been sealed.

Shrinkage Cracking

Transverse cracking of the type normally associated with slab shrinkage was observed in the asphalt concrete surfacing of many of the lime treated roadways reviewed in this study (see Figure 18). Both treated soils and treated aggregates were so affected but the chances of this type of cracking occurring seemed to be greater on projects where lime was used to treat the more granular materials. Sixty percent of the roads constructed with lime treated aggregates showed evidence of shrinkage cracking compared to only twenty percent of the roads constructed with lime treated soils. Also, all of the roads which had visible shrinkage cracking were in fair to good condition after ten years of service. Only one of these had required resurfacing other than planned stage construction prior to the end of ten years. Evidently, the lime treated materials which had visible shrinkage cracking generally provided a stronger structural section (slab effect) than other lime treated materials which were not as susceptible to shrinkage cracking.

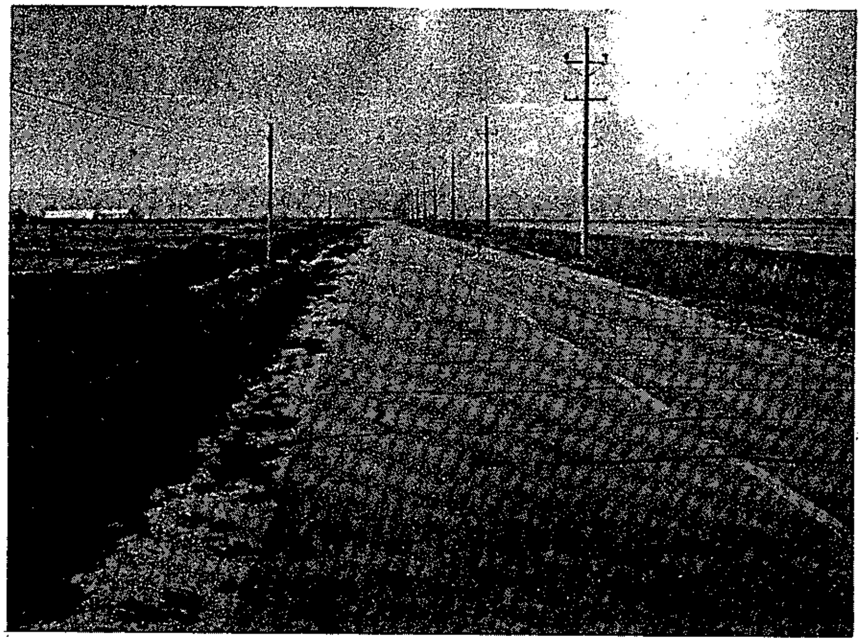


Figure 18
Shrinkage Cracking

These observations tend to substantiate previous conclusions by other researchers (8) that shrinkage type cracking on lime stabilized projects occurs most often when the treated base consists of low PI materials. It was theorized by McDowell that aggregate bearing mixtures consisting of high PI materials and lime are less fragile and can support loads with less cracking during curing than can low PI or more fragile mixtures.

It is probably not possible to eliminate shrinkage cracking altogether but it may be possible to reduce its magnitude and limit its effect on the surfacing. Shrinkage is caused in part by drying of the material. Observations in the field and in the laboratory both indicate that drying, especially rapid drying during the early stages of the chemical reaction, can result in severe cracking of the lime treated material. Severe shrinkage cracking was recently observed on a new subdivision street. The lime-treatment portion of the work was done during the mid summer and was left uncovered and unprotected while other work was being done. When reviewed several weeks after being placed, the lime-treated native soil was well cemented but broken into sections often 12 inches or less in size.

In another subdivision, two adjacent sections were constructed using identical structural sections. One portion was paved with asphalt concrete within a few days after completion of the lime treated base. The second portion was not paved for several weeks, but the lime treated base was protected with a curing seal during the interim. By the time this second portion was paved, shrinkage cracks were evident. Within a year after completion of the project, shrinkage cracks were visible throughout the first portion but none were evident in the second portion even after four years. Apparently cracking which developed after the asphalt concrete was in place reflected through the surfacing but when the surfacing was placed on the already cracked area it was not subjected to the same stresses and, therefore, did not crack.

These observations indicate not only a need for protection of the lime treated layer but also the possible desirablity of delaying paving until the lime treated material has undergone initial curing and the initial shrinkage has occurred. Extreme caution must be exercised to prevent excessive drying and associated shrinkage which could result in a loss of slab strength. This would be much more detrimental to the performance of the road than the shrinkage cracks that sometimes reflect through the asphalt concrete surfacing at regular intervals.

Preliminary Design Testing

The R-value test is used to evaluate the load bearing capacity of most materials in and below the roadway structural section. It is also used to calculate the required thickness of individual layers as well as the total structural section thickness.

With respect to lime treated materials, it is used to evaluate the increase in strength of the treated material and to determine the optimum amount of lime that would be necessary to achieve the greatest strength. Instances cited earlier, where obviously underdesigned roads have proven to be satisfactory and properly designed roads have failed miserably, indicate that the R-value test may not be providing an accurate measure of the effect of the lime treatment. Currently, thought is being given to tests involving triaxial principles, pulsating loads, or unconfined compressive strength.

It should be pointed out at this time that there are two primary reactions taking place when soil is treated with lime. First, there is an ion exchange between the positively charged calcium ions and the negatively charged metalic ions on the surface of the clay particles. This ion exchange can change a clay from a cohesive, plastic material to a friable, non-plastic material. The second reaction which occurs is a cementing action. As the lime combines with natural pozzolans in the soil, a chemical reaction takes place which is similar to the cementing action provided by portland cement. It is possible, however, that a material will respond to lime treatement by undergoing an alteration in characteristics without the cementing action following. Many engineers are of the opinion that when cementing occurs, it will be permanent. No evidence to the contrary was revealed in this study. The ion exchange, however, may not be permanent if cementing does not follow. There is then the possibility that if cementing does not take place, the total benefit of the lime treatment may be lost after a period of time.

Because the ion exchange is a rapid reaction, whereas the cementing continues at a relatively slow rate over a long period of time, the R-value test is only capable of providing an indication of the early improvement that can be expected by the change in material characteristics. This may explain why some roads have performed poorly despite the fact that preliminary tests indicated that lime treatment would satisfactorily improve the R-value of the material. Several of these roads were discussed in the section on nonresponsive materials. It was concluded there that the presence of certain elements in the soil were possibly responsible.

It must therefore be concluded that the R-value test does not provide enough information regarding the long term effects of lime treatment. Regardless of the ultimate strengths that may occur, the maximum achievable R-value for lime treated materials is approximately 90. Many untreated, crushed aggregates have R-values in this same range. The increase in R-value which occurs as different amounts of lime are added to a soil is typified by the two sets of data plotted in Figure 19. Both soils achieved approximately the same R-value when equal amounts of lime were added. Unconfined compressive strengths for these same two soils are also plotted in Figure 19. Quite obviously, the cementing action was much greater with the one soil than with the other.

In order to better evaluate the ultimate strength of a treated material, it is recommended that an unconfined compressive strength test be used. This would not only provide a better indication of a material's response to lime treatment but would also more adequately distinguish between various materials.

This could lead to even greater economies by allowing the design engineer to take full advantage of the strength of the treated material if it can be predicted.

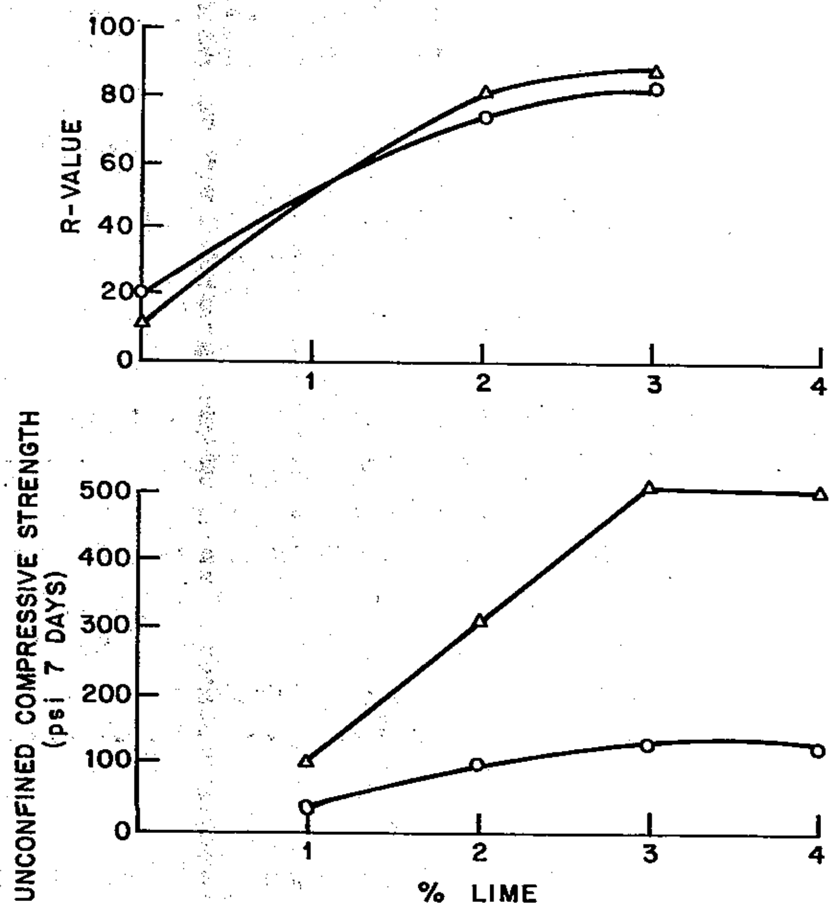
Evaluation of Design Procedures

Structural section design for the roads included in this study differed from project to project. The California design method was apparently used to design a good number of roads but in many instances the asphalt concrete thicknesses did not include a safety factor. Several others were built using stage construction with a portion of the asphalt concrete to be added at some future date. At least one county modified the California design method by assigning a greater gravel equivalent value to lime treated soils.

There were also many roads constructed to arbitrary thicknesses without benefit of materials or traffic evaluations. In most cases, these were light duty roads with very limited funds available for construction.

Figure 19

A COMPARISON OF THE EFFECT OF LIME TREATMENT ON THE R-VALUE AND COMPRESSIVE STRENGTHS OF TWO TYPICAL SOILS



Even though the actual design methods differed, all of the roads were compared and evaluated with respect to the California design method. These comparisons were presented earlier in Figures 2, 3, 5, 6, 8 and 9 and discussed in the section on Evaluation of Roadway Performance. It is concluded that the California design method does provide a structurally adequate road when the materials being treated with lime are susceptible to the treatment. In nearly all instances, roads which met the current design standards, including the safety factor, were in good condition after ten years of service. As the departure from the design requirements increased, the incidence of major distress and road failure also increased. This was especially true for the asphalt concrete surfacing.

There are also many examples of roads which performed satisfactorily despite the fact that they apparently had major "deficiences" in structural thickness. Some of this may have been due to less traffic than anticipated. It is concluded, however, that at least some of the good performance of under-designed roads was due to the treated material having more strength then allowed for with the assigned 1.2 gravel factor. Cores from various roads revealed that it is not unrealistic for a 4" x 4" specimen of lime treated material to have an unconfined compressive strength of 400-500 psi. One core was recovered which had an unconfined compressive strength of 2000 psi. Under these conditions, a thinner structural section should be structurally adequate.

It is concluded that the California design method provides for adequate structrual sections when responsive lime treated materials are used. It does not, however, take full advantage of lime treated materials which develop high unconfined compressive strengths. Since there was a wide range of compressive strengths observed during this study, any design thickness predicated upon an assumed compressive strength should not be used unless the assumed strength can be obtained under actual construction conditions.

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APPENDIX A

Detailed Investigations of Projects Which Included Lime Treated Subbase

Project S6

This county road was constructed in 1964 using a structural section consisting of 0.17 ft. asphalt concrete (AC), 0.50 ft. aggregate base (AB), and 0.92 ft. lime treated subbase (LTS). This section should have been adequate with the exception that the AC thickness was not increased to include a safety factor. Lime was added to the native soils to provide the lime treated subbase. The upper portion of the LTS was treated with 4% lime while the lower portion was treated with 3% lime.

When first reviewed four years after construction, the road appeared to be in near perfect condition except for short areas of distress at both ends of the project. Alligator cracking and rutting were extensive for about 200 feet but no other distress was observed. By the fall of the following year, the magnitude of the distress in these areas had increased and several other areas of visible distress had begun to appear. The distress continued to progress at such a rate that by the time the road had been in service ten years alligator cracking had become widespread throughout the project and the pavement condition was rated as extremely poor. Rutting appeared to be minimal but the pavement was breaking loose at some locations and leaving pot holes (see Figure 20). Several deficiencies in the aggregate base material were revealed through coring and laboratory studies of the recovered materials. Laboratory tests on the base material from three sampling sites indicated R-values of 69, 73 and 79. The specifications normally require a minimum R-value of 78. When tested at the same moisture content as found in-place on the road, the R-value of one sample dropped from 73 to 66. Based on an R-value of 66, the required thickness of the asphalt concrete would have been over 0.25 ft.

Figure 20
Alligator Cracking and Potholing

At each sampling location, except the one in the area of the most severe distress, the lime treated subbase material was well cemented and free of any observed cracking. Unconfined compressive strengths of the core samples varied from 160 psi to 430 psi. The thickness of the layer, however, varied from 0.50 ft. up to the planned thickness of 0.92 ft.

Since no cracking was observed in the lime treated material, it is concluded that the distress visible on the surface is occurring primarily as a result of deficiencies in the aggregate base which in turn added undue stress to the asphalt concrete.

Project S14

This county road was constructed in 1962 on flat, level ground near San Pablo Bay. The designed structural section, consisting of 0.25' AC, 0.50' AB, and 0.92' LTS met all of the current California design criteria except that the AC thickness included only a portion of the designated safety factor. When reviewed after seven years of service, it was observed that distress was present to some degree over a major portion of the road. Areas of alligator cracking and potholes were observed in each of the four traffic lanes (see Figure 21). Irregular longitudinal cracking and spalling of the asphalt concrete surfacing were also present over much of the area. Because of the extensive distress, this road was rated as extremely poor.

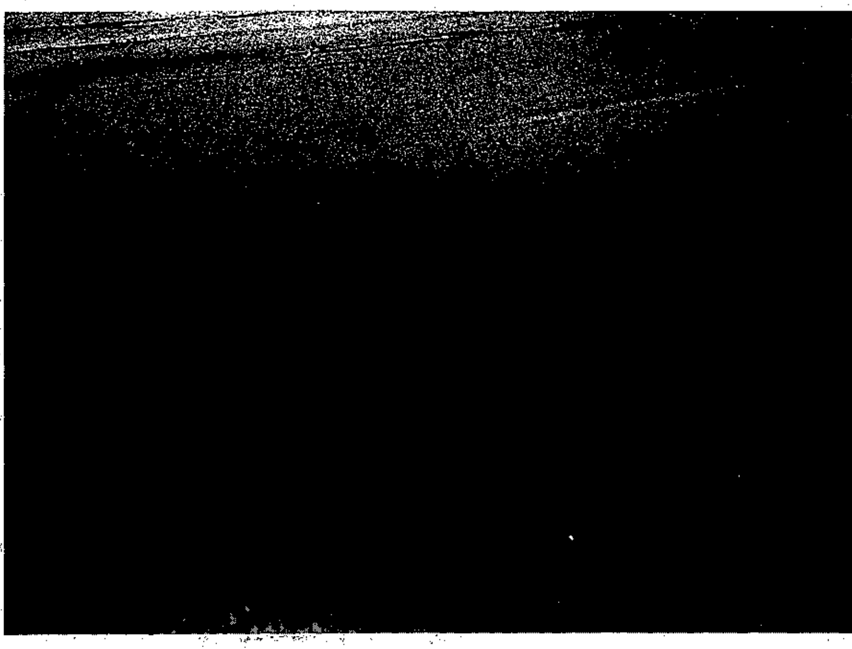

Figure 21
Alligator Cracking

Two locations were selected for coring and testing of the in-place materials. The first location was in an area where several irregular longitudinal cracks were visible in the travel lanes but there was very little evidence of alligator cracking. The aggregate base at this location was only 0.27' thick and the lime treated subbase was not uniformly cemented. Although the lime treated material was cemented in the top and bottom portions of the layer, the middle 0.24' of the layer was a soft pliable clay making it impossible to obtain core samples. Phenolphthalein indicator applied to the sides of the test hole turned bright red in the upper and lower portions, indicating the presence of lime. There was no color change indicating lime in the middle portion. This was also confirmed by chemical analysis which indicated approximately 4.5% calcium oxide (CaO) in the upper and lower portions but less than 1% in the middle. The CaO content of the untreated basement soil at this location was determined to be 0.7%.

The second sampling location was selected in an area where there was considerable alligator cracking. Again, the aggregate base was only 0.26' thick and the lime treated subbase was not uniformly cemented. At this location, the lower 0.35' of the LTS was cemented and laboratory analyses indicated a calcium oxide content of 3.2% and an R-value of 80. It was determined that the middle and upper portions of the LTS layer had CaO contents of 2.9 and 1.9, and R-values of 55 and 41, respectively. The asphalt concrete met minimum thickness requirements at both sampling locations.

A trench cut by a utility company provided an opportunity to inspect the structural section at a third location. Through this area, the lime treated material appeared to be well cemented. The foreman of the utility crew reported that the lime treated layer was so well cemented that they had experienced extreme difficulty breaking through this layer with their backhoe.

Based on these observations and findings, it is concluded that the distress on this project was due primarily to poor distribution of the lime during construction and a deficiency in the aggregate base thickness. The native soil was susceptible to lime stabilization but nonuniform distribution of the lime left inadequately treated layers or pockets of soil which were lacking in load bearing capacity. The deficiency in the thickness of the aggregate base compounded the potential problem by not providing adequate cover to bridge the pockets or layers of poor quality lime treated soil.

Project S18

This county road was constructed using a structural section consisting of 0.25 ft. AC, 0.50 ft. AB, and 0.92 ft. LTS. When reviewed after seven years, the surface of the road was totally free of any visible distress.

Since the entire road was in excellent condition, two locations were arbitrarily picked for a detailed investigation of the in-place materials. At both locations, the thickness of the asphalt concrete and the quality and thickness of the aggregate base met or exceeded all requirements. The LTS at the first location was extremely hard and proved to be impossible to cut through with an air-hammer. Cores removed from this material were found to have compressive strengths of approximately 2000 psi.

At the second location, there was no cementing of the lime treated material. Laboratory tests, however, indicated that this material had a minimum R-value of 51 which was still adequate for the design conditions.

A chemical analysis of the materials indicated calcium oxide contents of 4.5 and 3.4 at locations 1 and 2 respectively. It is not believed that this difference alone would account for the variations in cementing.

Figure 22
Pavement in Excellent Condition After Seven Years

The construction records state that there was some problem with the treated material quaking under construction traffic. It was concluded that this was caused by an excess of water and, after a few days, most of the areas had firmed up. In a few isolated areas, additional lime was added to the remaining soft spots to assure adequate stabilization. The records do not identify these areas but it is possible that the first sampling location was within an area where additional lime was used. It is also possible that the lack of cementing at the second location was the result of the excess water which resulted in insufficient compaction and allowed movement within the layer, thus destroying any cementing action as it developed.

There is also the third possibility that the material at the second location was not responsive to lime treatment. This possibility was discussed in greater detail in the section of this report titled "Nonresponsive Materials".

Projects S2 and S3

Two adjoining portions of this FAS road were constructed concurrently using structural sections consisting of 0.12' AC, 0.50' AB, and 0.50' or 1.00' of LTS. The material used as LTS included in-place roadway materials, selected excavation materials, and imported aggregates. Because of the variations in the type of material used in the subbase layer, the R-values of the untreated materials ranged from 6 to 74. There was no record of the location of where the various materials were placed.

After ten years of service, both sections of road were in generally good condition. Transverse and longitudinal cracking were observed at 5 to 15 ft. intervals over most of the roadway and distress in the form of alligator cracking and rutting was visible only in isolated areas. Even though the transverse cracks were often quite wide, there was no apparent distress in conjunction with them. In some areas, a narrow but abrupt depression in the surface had developed along the irregular path of the longitudinal crack.

A deflection survey was made over four 500 ft. test sections using the traveling deflectometer (9). Two of the test sections included areas where alligator cracking was visible. In the uncracked areas, the deflection measurements were generally less than .035 in., while deflection measurements in the distressed areas ranged from .030 to .050 in. with most measurements greater than .038 in.

Three locations were selected for coring and testing of the structural section material. The first location was selected from an area where there was no visible distress other than the transverse cracks. Even though the lime treated material appeared to be well cemented, it was not possible to recover a good core sample of the layer because of horizontal separations into the layers of 2 inches or less in thickness.

The second location was selected from an area where a longitudinal crack, accompanied by surface depression and transverse cracking, were the only visible distress. At this location, the lime treated layer was well cemented and cores with a minimum length of four inches were recovered. The unconfined compressive strength of the lime treated material at this test site was determined to be 1000 psi. The longitudinal and transverse cracks visible in the surfacing at both locations 1 and 2 were traced all the way through the lime treated layer. There was no evidence of any irregularities in the surface of the lime treated material, even along the noted cracks. The surface depression along the crack appeared to be the result of a loss of aggregate in the base course.

The third coring location was selected from an area which was badly rutted and severely cracked. The untreated aggregate base at this location was approximately 0.33' thick in lieu of the planned 0.50', and the upper 0.67' of the planned 1.0 ft. lime treated layer was not cemented. Approximately 0.20' of well cemented lime treated material was found below the soft upper portion. A chemical analysis of the recovered materials showed, however, that the soft clayey material in the LTS layer at this location contained approximately 3.0 percent calcium oxide (CaO) while the 0.2' of well cemented material contained 3.8 percent CaO. A chemical analysis of the LTS layer at locations 1 and 2 indicated calcium oxide contents of 4.1 and 4.5 percent. In addition to containing somewhat less calcium oxide, the LTS at location 3 was a much finer material than that found at locations 1 and 2. It is not possible to assign a definite cause for the poor quality of the lime treated material at lcoation 3 but a combination of the reduced amount of lime along with the increased amount of clay in the soil may have resulted in insufficient lime to complete the stabilization process.

Other factors such as continued working of the material after cementing had begun or insufficient compaction could also have contributed to the poor quality of the LTS but no records are available to substantiate these possibilities. The aggregate base thickness deficiency no doubt also contributed to the distress to some extent.

Project S8

This FAS project was constructed using a structural section consisting of 0.17 ft. AC, 0.50 ft. AB, and 1.00 ft. LTS. Four percent hydrated lime was added to the in-place materials, primarily native soils, to provide the LTS.

Even though traffic had probably exceeded the design T.I. and the stage 2 surfacing had not been placed, the surface condition of this road was generally good after ten years of service. There were, however, a few areas near the outer edges of the pavement where alligator cracking and rutting were visible.

The structural section materials were sampled from two selected locations. One of these was in an area where some cracking was developing.

The recovered aggregate base material at both locations was within allowable tolerances for quality and thickness. At the location where there was no visible distress, the LTS was well cemented and compressive strengths of 225 psi and 400 psi were measured. At the location where some distress was visible, the lime treated material was not solid enough to core. Although cementing had occurred, the material broke out in pieces rather than as a unit, indicating that cementing had not been uniform or possibly that the slab had been broken up. When this broken and loose material was recompacted and tested, it was found to have an R-value of 78 which was more than adequate for use as a subbase.

During the sampling of the structural section materials at both locations, a thin layer of clayey material was observed on the surface of the LTS. It was also observed that a definite grading plane existed between the two lifts of the LTS layer. Both of these observation are discussed more fully in other sections of this report.

APPENDIX B

Detailed Investigation of Projects Which Included Lime Treated Aggregate as a Base

Project BA7

This project consisted of adding several miles of passing lanes to U.S. Highway 50 in the Sierra Nevadas. The as-built structural section consisted of 0.25' AC over 0.67' of lime treated decomposed granite obtained from a site within the limits of the project.

Prior to treatment with lime, the selected material was required to have a minimum R-value of 65 and a minimum sand equivalent (10) of 25. Hydrated lime was added at a rate of 5 percent by dry weight of the aggregate. Construction control tests indicated that the treated aggregate had an R-value in the high 70's or 80's.

The constructed structural section provided a total thickness which should have been adequate for use over a 53 R-value basement soil even though the asphalt concrete surfacing was deficient in thickness. To meet the minimum AC requirement, excluding a safety factor, a thickness of 0.30 ft. would be required in lieu of the 0.25 ft. placed. To satisfy the safety factor requirement, a total of 0.40 ft. of AC was needed.

Test holes were cut at three locations on this job. One was in an area where extensive alligator cracking was observed and the other two were in areas where the surface condition appeared good.

Core samples could not be cut at any of the three selected locations. At the first two locations there was no cementing of the treated layer whatsoever. The top portion of the treated material placed at the third location broke into fairly hard lumps but was not solid enough to permit recovering a core sample.

It was learned from these test holes that this road had been resurfaced on several occasions since original construction. At the first location, the AC was 0.60 ft. thick. At the second location, three distinct layers of AC were observed on top of the original pavement. At the third location, where there was some cementing of the lime treated base, the road had been resurfaced only once.

Laboratory tests on materials recovered from the three test sites revealed a lack of uniformity in the quality and quantity of the lime treated layer. At the first location, the upper 0.30 ft. of the LTB had an R-value of 80 and a calcium oxide content of 5.2 percent. The lower portion of this same layer had an R-value of 73 and a calcium oxide content of only 0.4 percent. At the second location, insufficient material was recovered to perform R-value tests but the calcium oxide content of the treated layer was only 0.1 percent. Material from the third location had R-values of 83 and 80, respectively, in the upper and lower portions of the layer and calcium oxide contents of 3.0 and 2.2 percent.

Poor distribution of the lime may have contributed to the observed distress and the repeated need for resurfacing on this project; however, the primary problem was probably a deficiency of clay and natural pozzolans in the clean decomposed granite.

Project BA9

A 2.4 mile section of this State highway was constructed in 1960 using a structural section consisting of a double seal coat over 1.0 ft. of imported base material (IBM) having a minimum R-value of 60. In 1961 three segments of this section, totaling 1825 ft., were reconstructed by treating the top 0.5 ft. of the IBM with 5 percent lime and adding 0.10 ft. of asphalt concrete surfacing. An 0.08 ft. thick AC blanket was added to the entire roadway in 1966. When reviewed in 1968, longitudinal and transverse cracking was evident throughout the lime treatment areas. When reviewed again in 1975, fourteen years after lime treating the base, the lime treated areas were in about the same condition; transverse and longitudinal cracks at 10 to 15 ft. intervals but no other distress. The adjacent sections, however, which had not been lime treated, were developing severe alligator cracking over much of the surface area. Thus, the lime treatment had apparently strengthened the structural section significantly.

Project BA4

This road was not cored for detailed analysis, but because of severe pavement distress which necessitated resurfacing before the end of its ten year design life, the following information is offered. A four and one-half mile section of this road was constructed as a Federal Aid Secondary project in 1959. The structural section consisted of 0.25 ft. AC over 1.00 ft. of LTB and met design formula requirements. The mineral aggregate used in the LTB had a specified minimum R-value of 35 prior to treatment.

This entire road from Truckee to Kings Beach was later incorporated into the State Highway System. Because of the improved alignment and grade, the road soon become a popular short-cut between Interstate 80 and Lake Tahoe and carried a high volume of buses and trucks. Logging trucks hauling timber from the forests in this area also contributed to the high traffic volume.

An 0.08 ft. AC blanket was placed in 1967, eight years after construction, because of distress in the pavement. Even so, with the high volume of trucks and buses then using this road, it may have carried the total volume of design traffic in the shorter period.

APPENDIX C

Detailed Investigation of Projects Which Included Lime Treated Soil as a Base

Projects BS3 and BS22

This county road was constructed in two portions; the first in 1961 and the remainder in 1964. Both portions were constructed using lime treated native soil as both a base and a subbase. The only difference between the base and subbase was the amount of lime added. Three percent lime was added to the lime treated base (LTB) layer and two percent was added to the lime treated subbase (LTS) layer. Preminary tests indicated that these concentrations of lime would raise the R-value of these native soils from 17 and under to over 80 with 2 percent and to over 87 with 3 percent.

The planned structural sections for the two portions of road differed only slightly. The planned section for the first portion consisted of 0.15 ft. road mixed asphalt surfacing (RMAS), 0.50 ft. LTB, and 0.58 ft. LTS. The planned section for the second portion consisted of 0.13 ft. RMAS, 0.50 ft. LTB, and 0.50 ft. LTS.

Six years after construction of the first portion, the county found it necessary to resurface this portion of the road because of rutting and cracking. Even so, the lime treatment was considered a success. This area had always been subject to high ground water and considerable differential settlement. As a result of the lime treatment, maintenance requirements had been significantly reduced. The second portion of this road was also resurfaced at about the same time but an appraisal of its condition at the time was not available.

Regardless of the reasons for resurfacing, the additional asphalt concrete did no more than increase the total surfacing thickness to that required by the design standards for a 7.0 traffic index. The first portion was in poor condition again by the time it had been in service a total of nine years and the second portion was in poor condition by the time it had been in service five years.

Deflection measurements in 1971 varied from .012 to .062 inches with the higher deflections in the newer portion of the road.

Four test sites were selected for coring, two in each portion of the road. For the most part, the coring was unsuccessful. Both attempts in the newer portion of road revealed insufficient cementing of the treated material to cut a core. In the older portion, there was some cementing of the treated material but there was still separation into layers, thus making it impossible to determine compressive strengths.

Because of the lack of cementing of the treated material, it was difficult to distinguish and measure the thickness of the individual layers. Changes in texture, separation on horizontal planes, cementing or lack of cementing, and color reaction with phenolphthalein indicator all offered some clues as to the different layers. On this basis, it was determined that the total thickness of the two lime treated layers was generally deficient by approximately 0.3 ft.

R-values determined in the laboratory on material recovered from the LTB layer were 63, 80, 84 and 72 respectively for the four test sites; all below the 87 indicated by preliminary testing. The LTB material recovered from Site 1 had a much higher in-place moisture content than that assumed for a routine R-value test. When tested at this moisture content, the R-value dropped from 63 to 30. The R-values determined on material recovered from the LTS layer ranged from 65 to 68; significantly below the 80 indicated by preliminary tests.

Obviously, the stability of the native soils was greatly improved by the addition of lime, but in this case it was not sufficiently improved to provide a structurally adequate road.

Project BS29

This county road was constructed in 1966 with a planned structural section of 0.13 ft. RMAS, 0.5 ft. LTB, and 0.5 ft. LTS. The LTB and LTS both consisted of lime treated native soils, the only difference being the amount of lime added. Three percent lime was added to the LTB while two percent was added to the LTS.

Groundwater is near the surface in this area and there is considerable ground subsidence. As a result, this road has a history of requiring more than normal maintenance.

When first reviewed after only two years of service, this road was in extremely poor condition with an estimated 25 to 50 percent of the surface area being visibly distressed or already repaired.

Deflection measurements five years after construction varied from approximately .040 to .110 inches. Two test sites were selected on the basis of those deflection measurements. One was in an area where the deflections were lowest and the other where the deflection measurements were approximately .080.

No cementing of the treated material was evident at either test site. Material in the base at both sites was found to have an R-value of less than 30. The material in the subbase had an

R-value of less than 15. Quite obviously, lime treatment on this project was ineffective. Either the amount of lime added was insufficient to complete the reaction or the soil was not responsive to lime treatment.

Laboratory tests on the recovered materials showed calcium oxide (CaO) contents in the LTB and LTS layers varying from 2.05 to 3.10 percent. The significance of these measurements is questionable, however, because the CaO content of the basement soil under the road was measured to be 1.64 and 2.18 percent at the two test sites and native material sampled along side the road to a depth of 1.5 ft. had a CaO content of 2.56 percent.

Project BS25

This county road was constructed in 1965 using a structural section composed of 0.20 ft. AC and 0.50 ft. LTB. The LTB consisted of native soils treated with 4 percent hydrated lime.

When first reviewed three years after construction, the surface was judged to be in poor condition with alligator cracking and patching over a wide area. Deflection measurements indicated pavement deflections from .010 to 0.100 inches.

Two test sites were selected for coring and sampling the in-place materials. One site was in an area where the deflection was .070 inch and the pavement was severely distressed. The second site was in an area where the pavement appeared to be in excellent condition and deflections were less than .020 inches.

The asphalt concrete at both test sites was found to be 0.20 ft. thick as planned. The lime treated material at site one appeared to be cemented but broken chunks were interspersed with softer materials. At the second site there appeared to be better cementing of the total layer but the cores sheared off in layers approximately 1 1/2 to 2 inches thick.

Laboratory tests on materials recovered from the two sites indicated R-values of the lime treated layer to be 82 and 78. Untreated basement soils from the respective sites had R-values of 17 and 25. It was also observed that the basement soils contained considerable water. When tested at their in-place moisture content, the R-values of the untreated material were 8 and 9, respectively.

It was concluded that the primary reason for early distress on this road was underdesign of the structural section. Based on a design R-value of 15 and a traffic index of 7.0, a section having a gravel equivalent value of 1.9 ft. is required in lieu of the 1.03 ft. provided. Excessive groundwater and heavily loaded logging trucks were probably contributing factors to the poor performance.

Project BS11

This county road was constructed in 1964 with a planned structural section consisting of 0.12 ft. AC and 0.67 ft. LTB. The LTB was prepared by adding 4 percent hydrated lime to the native soil.

This low traffic volume road was observed to be in good condition each time it was reviewed; however, some localized distress in the form of alligator cracking and rutting was observed in a few areas.

Two test sites were selected for detailed investigation of the in-place materials on this project. Both sites were at the same station but one was in the outer wheel path where there was obvious rutting and cracking while the other was in the inner wheel path where there was no apparent distress.

The asphalt concrete surfacing in the outer wheel path was found to be only 0.07 ft. thick while in the inner wheel path it was 0.18 ft.

The lime treated base was found to be poorly cemented and could not be cored. At both sites, there was a visual difference between the upper and lower portion of the treated layer. The top 0.18 ft. at each coring location was tested independently of the lower portion. Based on visual appearance, the total depth of the treated layer was determined to be 0.65 ft. and 0.90 ft., respectively, in the outer and inner wheel paths.

R-values were determined to be 51 and 69 for the top and bottom portions in the outer wheel path. The basement soil had an R-value of 23. In the area of the inner wheel path, the R-values for the top and bottom portions of the LTB were 48 and 83, and the R-value of the basement soil was 27.

Calcium oxide content determinations on the LTB materials indicated a lack of uniformity in the distribution of the lime. The top portion had measured CaO contents of 2.9 and 2.7 percent while the lower portions had CaO contents of 3.7 and 4.7 percent respectively. These figures do not necessarily represent the amount of lime added since the basement soil at both locations had CaO contents of 1.9 percent. It does, however, indicate a variation in lime which corresponds to the variations in R-value. Thus, the pavement distress noted on this project was no doubt caused, at least in part, by nonuniform lime treatment and a deficient AC thickness.

Projects BS17 and BS18

Two segments of this Federal Aid Secondary road were constructed in 1965 using a structural section consisting of 0.34 ft. AC and 1.25 ft. LTB. The asphalt concrete was planned as stage construction with 0.17 ft. being placed at the time of original construction. The second stage was not actually placed until seven years later. The LTB consisted of native soils having R-values as low as 3, some existing roadway materials, and 4 percent lime.

Visual observations indicate that both segments of this road performed satisfactorily with the exception of some localized distress (see Figure 23). Most of the severe distress, in the form of alligator cracking and rutting, developed in a one quarter mile section of the total three and one-half miles constructed. Deflection measurements varied from .003 to .039 inches with the higher deflections in the obviously distressed areas.

Figure 23
Alligator Cracking and Rutting

Two test sites were selected for sampling and testing the in-place materials. One was in an area of high deflections and obvious distress while the other was in an area of low deflection and no visible distress. The thickness of AC at the two sites was 0.16 and 0.18 ft. respectively.

The LTB at the first site contained alternate layers of cemented material and soft plyable clay, making it impossible to obtain a full 4-inch core sample. A 2-1/2 inch high portion of a core was recovered, however, and when tested in the laboratory had an unconfined compressive strength of 290 psi. R-values of the various layers varied from 15 to 82 when tested at their in-place moisture contents.

At the second site, the top ten inches of LTB was well cemented and a core sample was recovered. The lower portion, however, broke up quite severely. The compressive strength was not determined directly on this core but instead a split tensile strength (<u>11</u>) of 35 was measured. This value is estimated to indicate an unconfined compressive strength of approximately 250 psi. When the cemented LTB was broken up, remolded, and tested in the laboratory, an R-value of 78 was measured.

The soil on this project was determined to be suitable for lime stabilization. It was concluded that the distress was the result of incomplete distribution of the lime within the soil.